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of

THE ROYAL AERONAUTICAL SOCIETY

MARCH 1954

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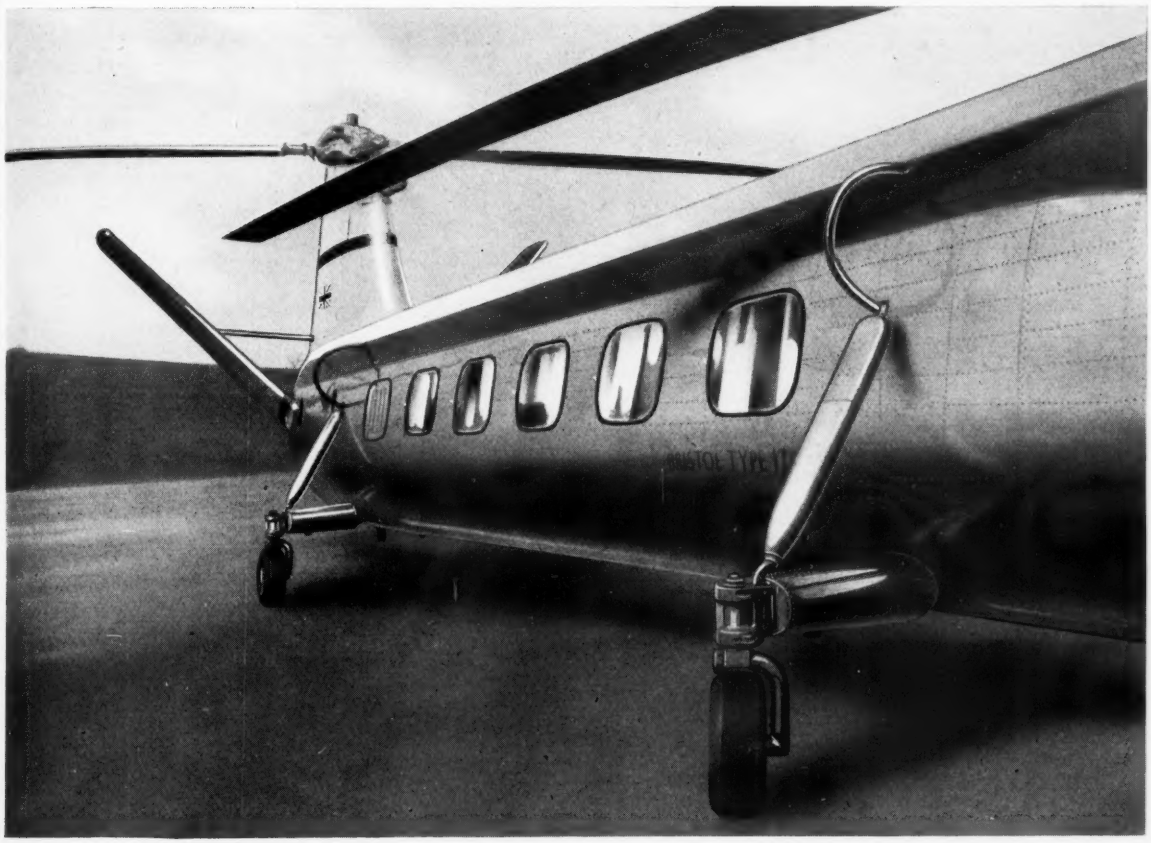

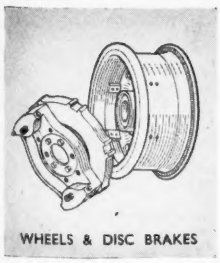

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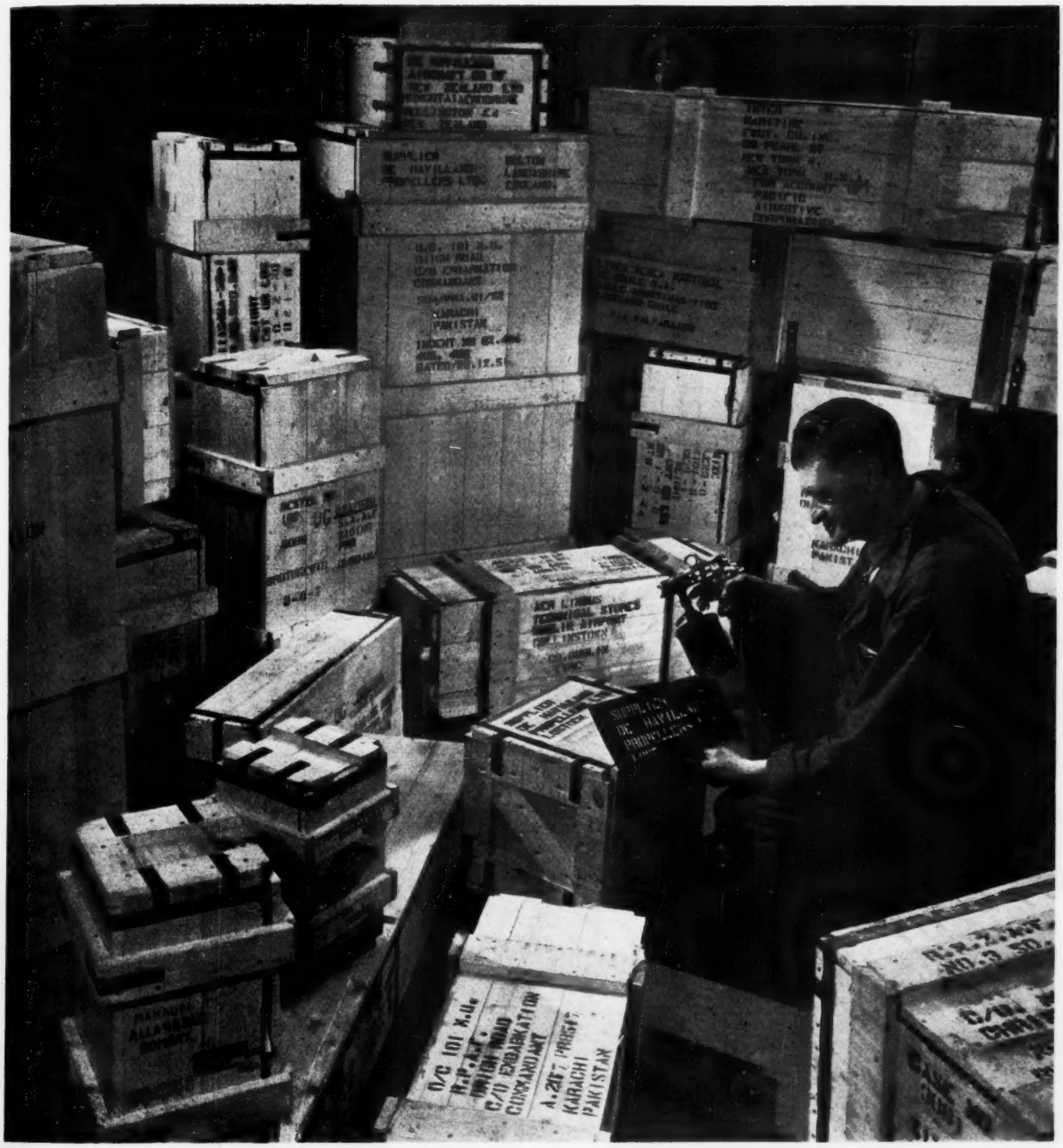

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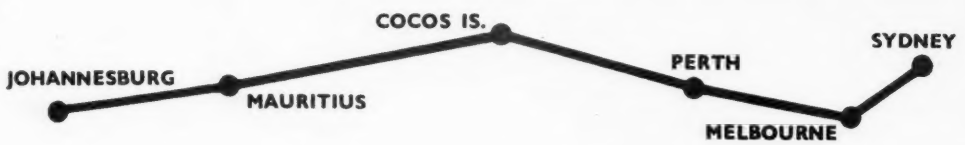

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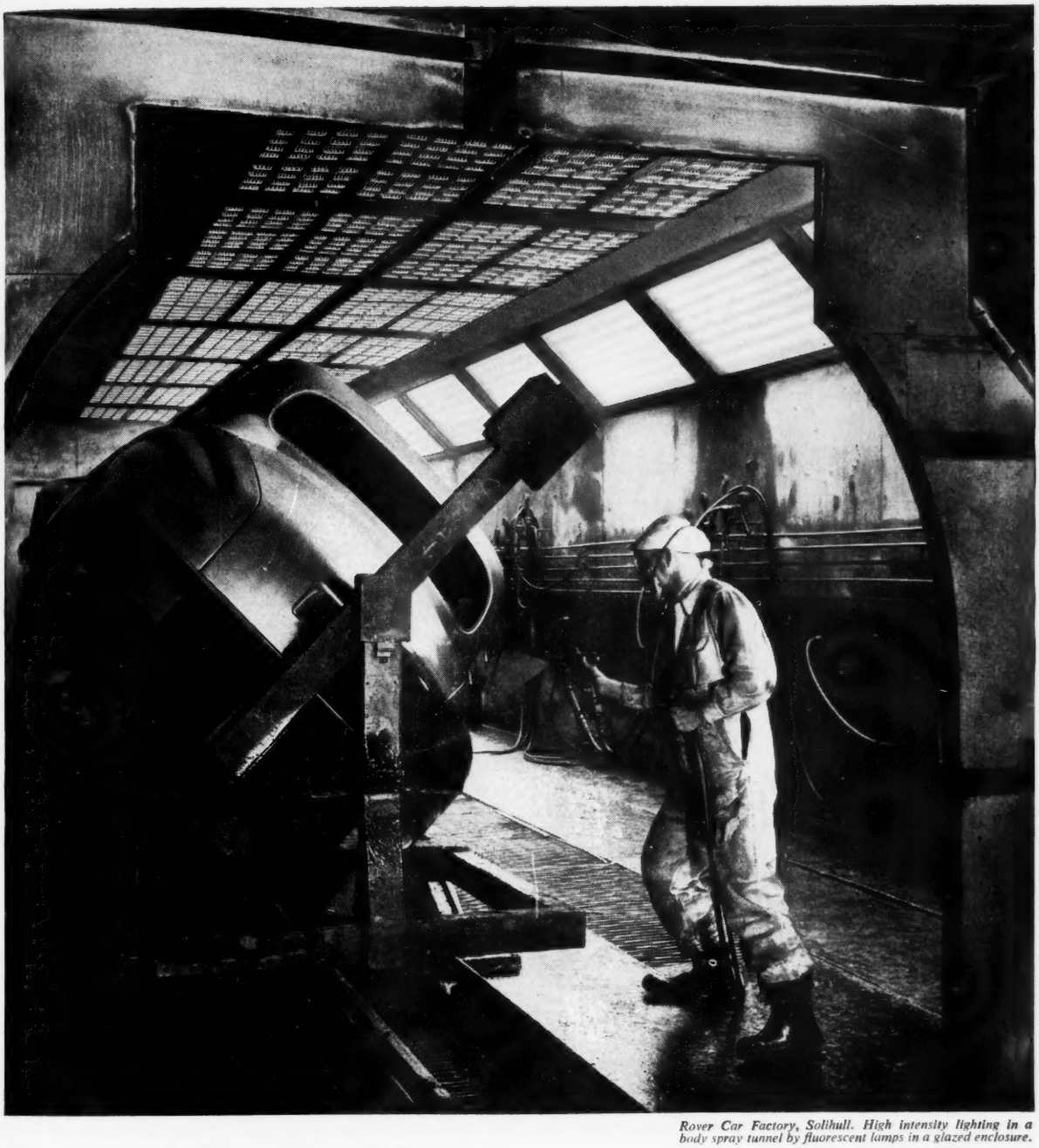

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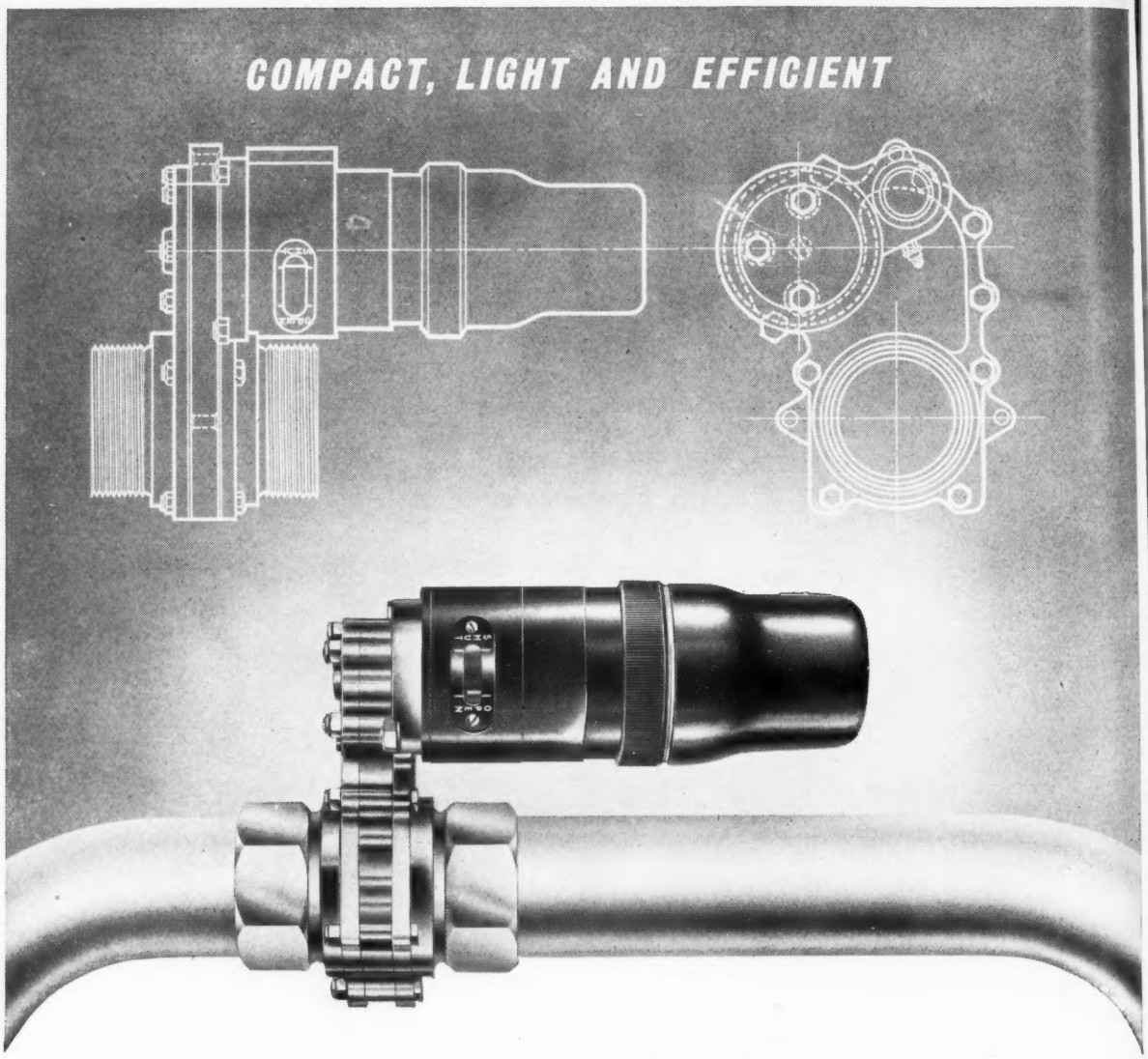

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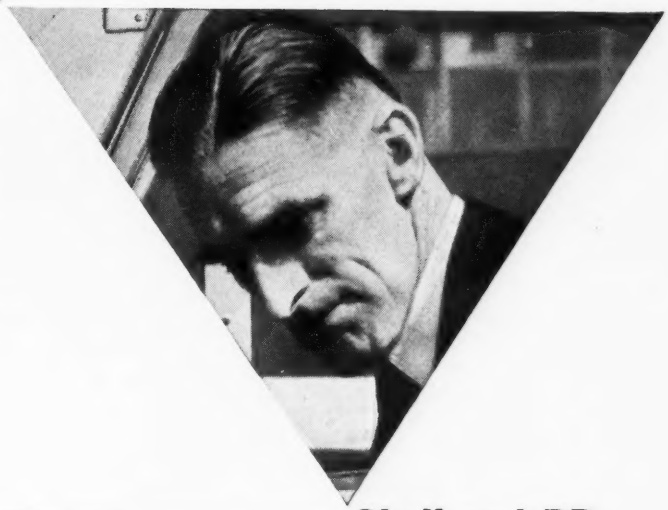

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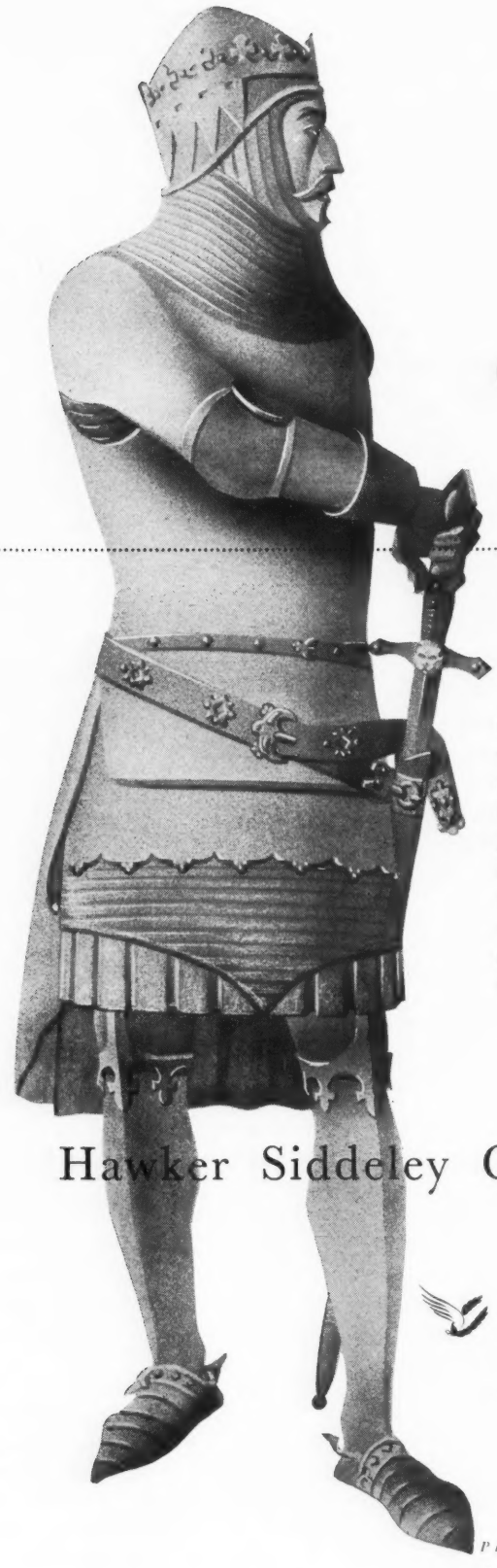

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YEOVIL

Hon. Secretary: L. A. LANSDOWN, A.F.R.Ae.S., Westland Aircraft Ltd., Yeovil.

Journal of

THE ROYAL AERONAUTICAL SOCIETY

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None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless stated otherwise.

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Secretary's News Letter

March 1954

AFTER SERVING as Honorary Treasurer for eight years, Mr. C. F. Uwins has resigned from this office owing to his extremely heavy business commitments. His resignation was accepted with much regret by the Council. Mr. Uwins devoted much time and energy to his duties as Treasurer, and I am sure all members of the Society will wish me to tell him our appreciation and thanks for his zealous work on behalf of the Society, and to wish him well in the future.

Major G. P. Bulman has been invited to replace Mr. Uwins as Honorary Treasurer, and I am pleased to say that Major Bulman has accepted.

On 17th February I paid my first visit to the Manchester Branch, and attended the lecture by Mr. S. Allen on "The Rocket Power Plant." The President, Sir William Farren, was introduced by the Branch Chairman, Mr. C. E. Fielding, and he said a few words. Sir William took the opportunity of emphasising to the audience that membership of the Society was open to those engaged on any of the many aspects of rocket development. Attention was drawn to the Section Lecture by Mr. G. O. Jones on 6th April at Hamilton Place, on "A Review from the Design Aspect of Materials used in Rocket Motors."

During my visit to Manchester I saw over the works of A. V. Roe, escorted by Mr. Fielding at Chadderton, and Sir William and Mr. L. E. Leavy at Woodford. I was interested in the use of concrete to give weight to formers. I inspected some of the Test Rigs; the structural rig is large, larger than a "cathedral," I was informed. To give it a name it would appear that they will have to depart from the present nomenclature and go to the fields for meeting places; although not strictly a place, by a slight transference of idea it might be called a "conventicle."

I have been adding up the number of Branches I have visited, and I find that, in this country, there is only one still to be visited. I shall not name it, but I hope to make arrangements to complete the number in the near future.

The B.B.C. made recordings of the speeches at the Commemorative Dinner on 17th December 1953. I have had copies made and these are available on loan. There are fourteen records, each of about four minutes, and the complete run through lasts about one hour.

A. M. Ballantyne

Secretary

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Annual General Meeting, 6th May 1954

Notice is hereby given that the Annual General Meeting of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, will be held on Thursday 6th May, at 5.30 p.m. in the offices of the Society, 4 Hamilton Place, London, W.1.

Agenda

1. To read the Notice convening the Meeting.
2. To receive and deliberate upon the Report of the Council on the state of the Society and the Balance Sheets and Income and Expenditure Accounts of The Royal Aeronautical Society and Aeronautical Trusts Limited for the year ended 31st December 1953.
3. To receive the names of those elected to Council for the years 1954-57.
4. To announce the names of Fellows elected by the Council in accordance with By-Law 4.
5. To elect the Auditors for the year 1954.
6. Any other business.

By Order of the Council
A. M. Ballantyne,
Secretary.

NOTE.—In accordance with the By-Laws any member whose subscription has not been paid before the first day of April is not entitled to vote.

Light refreshments will be served after the meeting.

News of Members

Wing Commander H. Clarke (*Associate Fellow*) has been appointed Technical Superintendent at No. 10 Maintenance Unit. He has now retired from the R.A.F.

C. Dee (*Associate Fellow*) has been appointed Development Engineer to the Plessey Co. Ltd., Ilford. He was formerly with Teddington Controls Ltd.

Dr. K. H. Doetsch (*Associate Fellow*) has been promoted to Senior Principal Scientific Officer to fill the post of Superintendent, Control Division, Instruments and Air Photography Department, Royal Aircraft Establishment.

Air Commodore L. R. S. Freestone (*Associate Fellow*) has been appointed Director of Technical Services (Air), British Joint Staff Mission, Washington, D.C. He is at present Director of Armament Engineering at the Air Ministry.

T. Haas (*Associate Fellow*) has recently joined the Bristol Aeroplane Company Ltd., Aircraft Division, and is responsible for the Fatigue Section of the Engineering Laboratory, Filton.

J. A. Hasler (*Associate*) has taken up an appointment as Service Manager of Integral Limited, Wolverhampton.

M. B. Morgan (*Fellow*) has been appointed Deputy Director of the Royal Aircraft Establishment, Farnborough.

W. H. Stephens (*Associate Fellow*) has been appointed Head of the Guided Weapons Department, Royal Aircraft Establishment, Farnborough.

Dr. E. W. Still (*Fellow*), formerly Research and Development Manager at Teddington Controls, has been appointed Technical Director of Normalair Ltd.

E. K. Wellsted (*Associate Fellow*) has been appointed Chief Inspector to Percival Aircraft Ltd.

Air Commodore Sir Frank Whittle (*Fellow*) has taken up an appointment with the Bataafsche Petroleum Maatschappij of The Hague, Holland.

D. E. Williams (*Associate Fellow*) has been appointed as an Experimental Officer at the Ministry of Supply National Gas Turbine Establishment, Pyestock, near Farnborough.

Nomination of Candidates for Council, 1954

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than *10th April* in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be voters."

Nomination forms may be obtained on application to the Secretary.

Seventh Louis Bleriot Lecture

The Seventh Louis Bleriot Lecture will be held in Paris on Wednesday 10th March 1954, when Mr. R. Hafner, A.F.R.Ae.S., Chief Designer-Helicopters, Bristol Aeroplane Company, will lecture on "The Domain of the Helicopter."

The Lecture will be held at 5 o'clock in the Salle des Anciens Elèves des Ecoles d'Arts et Métiers, 9bis Avenue d'Iéna, Paris XVIe.

The Fifth Anglo-American Aeronautical Conference 1955

The Council of the Royal Aeronautical Society has pleasure in announcing that the Fifth Anglo-American Conference will take place in Los Angeles, California, in June 1955, under the auspices of the Royal Aeronautical Society and the Institute of the Aeronautical Sciences. Further information will be given as soon as it becomes available.

Institute of the Aeronautical Sciences

In addition to the awards mentioned last month, the following Fellows of The Society have been awarded Fellowships by the Institute of the Aeronautical Sciences:

Mr. L. P. Coombes, Chief of Aerodynamics, Aeronautical Research Laboratories, Australia, and

M. Maurice Roy, Director of the Office National, d'Etudes et de Recherches Aeronautiques (O.N.E.R.A.), France.

Additional New Year and Coronation Honours

The following awards were made in addition to the lists already published:

G. Tilghman Richards (*Fellow*) was awarded the M.B.E. in the Coronation Honours List. He has recently retired from the post of Official Lecturer on the Engineering and Industrial Collections of the Science Museum.

Squadron Leader D. de Villiers (*Graduate*), Commanding Officer of 500 (County of Kent) Squadron, R.Aux.A.F., and Chief Test Pilot of de Havilland Propellers Ltd., was awarded the Air Force Cross in the New Year's Honours List.

Acknowledgment

The Council acknowledge with thanks the return of back numbers of the Journal from S. W. Slaughter, Esq., *Associate Fellow.*

Diary

LONDON

March 10th

PARIS.—THE SEVENTH LOUIS BLERIOT LECTURE. The Domain of the Helicopter. R. Hafner.

GRADUATES' AND STUDENTS' SECTION. Annual General Meeting. 7.30 p.m. Followed by the film, "Powered Flight—The Story of the Century," 4 Hamilton Place, W.1. Coffee, 7-7.30 p.m. *Admission to the film is by ticket only.*

March 16th

SECTION LECTURE. The Development of the Spill Flow Burner and its Control System for Gas Turbine Engines. F. H. Carey. In the Library, 4 Hamilton Place, W.1. 7 p.m.

March 25th

GRADUATES' AND STUDENTS' SECTION. Airworthiness Requirements for Landing and Take-off. L. J. W. Hall. In the Library, 4 Hamilton Place, W.1. 7.30 p.m.

March 30th

SECTION LECTURE. Interaction between Shock Waves and Boundary Layers and its Importance in High-Speed Flight. Dr. D. W. Holder. 4 Hamilton Place, W.1. 7 p.m.

April 6th

SECTION LECTURE. A Review from the Design Aspect of Materials used in Rocket Motors. G. O. Jones. 4 Hamilton Place, W.1. 7 p.m.

April 8th

MAIN LECTURE AT THE CHESTER BRANCH. Practical Experience of Airline Engineering. R. C. Morgan. Grosvenor Hotel, Chester. 7.30 p.m.

April 13th

SECTION LECTURE. Some Aspects of Modern Aircraft Materials. Dr. H. Sutton. 4 Hamilton Place, W.1. 7 p.m.

April 22nd

MAIN LECTURE. Diesel Compound Engines. E. E. Chatterton. At the Institution of Mechanical Engineers, Storey's Gate, S.W.1. 6 p.m. (Tea 5.30 p.m.)

April 27th

SECTION LECTURE. Aerodynamics and Aeroelastic Characteristics of the Crescent Wing. G. H. Lee. In the Library, 4 Hamilton Place, W.1. 7 p.m.

April 29th

GRADUATES' AND STUDENTS' SECTION. Fuselage Structural Design Methods. R. J. Jupe. 4 Hamilton Place, W.1. 7.30.

May 4th

SECTION LECTURE. Propellers for High-Speed Aircraft. G. C. I. Gardiner. In the Library, 4 Hamilton Place, W.I. 7 p.m.

May 20th

THE 42ND WILBUR WRIGHT MEMORIAL LECTURE. The Choice of Power Units for Civil Aeroplanes. Dr. A. E. Russell.

BRANCHES

March 10th

Southampton.—The Design of Target Aircraft. R. J. B. Woodhams. Institute of Education, University of Southampton. 7 p.m.

March 13th

Birmingham.—Annual Dinner. Imperial Hotel, Temple Street, 6.15 for 6.45 p.m.

March 15th

Derby.—Social Function. Rolls-Royce Welfare Hall. 6.15 p.m.

Halton.—Branch Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

March 17th

Hatfield.—Integral Construction. E. D. Keen. de Havilland Restaurant, Hatfield. 6.15 p.m.

Manchester.—Sandwich Construction Applied to Aircraft Structure. W. G. Heath. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

Preston.—Aircraft Production Control. F. H. E. Maidment. Technical College, Preston. 7.30 p.m.

Weybridge.—Operating Viscounts. Captain A. S. Johnson. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.

March 18th

Isle of Wight.—Branch Prize Lectures. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, East Cowes. 6.30 p.m.

March 22nd

Halton.—Junior Members' Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

Henlow.—Student Members' Lectures. R.A.F. Technical College, Henlow. 7.30 p.m.

March 23rd

Belfast.—Some Aspects of Resistance Strain-Gauging. G. A. Lewis. Reception Room, Kensington Hotel, Belfast. 7 p.m.

March 24th

Gloucester and Cheltenham.—Current Problems in the Design of Wheel Brakes for Aircraft. D. A. J. Harben. Joint Lecture with the Institution of Mechanical Engineers. Wheatstone Hall, Gloucester. 7.30 p.m.

March 26th

Birmingham.—Lecture on Delta Aircraft. Birmingham Chamber of Commerce, New Street. 7.30 p.m.

Southampton.—Annual Dance.

March 31st

Bristol.—Aeronautical and Mechanical Engineering 1929-1954—A Retrospect and a Prospect. Wing-Cdr. T. R. Cave-Brown-Cave. Joint meeting with the Institution of Mechanical Engineers. Royal Fort Physics Laboratory, Bristol. 7 p.m.

Brough.—Annual General Meeting and Films. Lecture Hall, Electricity Buildings, Ferensway, Hull. 7.30 p.m.

April 2nd

Leicester.—Supersonic Bangs. G. M. Lilley. Loughborough College, Loughborough. 7.15 p.m.

April 5th

Derby.—Some Aspects of Airline Flying with Jet Aircraft. Captain W. G. Johnson. Welfare Hall, Rolls-Royce. 6.15.

April 6th

Belfast.—Annual General Meeting and Film Show. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

Glasgow.—The Piston Engine and the Development Engineer. J. M. Marshall. Royal Technical College. 7.30.

April 7th

Bristol.—Annual General Meeting and Film Show. Conference Room, Filton House, Bristol Aeroplane Co. 6 p.m.

Weybridge.—Brains Trust. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.

April 8th

Chester.—MAIN SOCIETY LECTURE. Practical Experience of Airline Engineering. R. C. Morgan. Grosvenor Hotel, Chester. 7.30 p.m.

April 14th

Glasgow.—Annual General Meeting. St. Enoch Hotel, 7.30 p.m.

Hatfield.—Discussion Evening. de Havilland Restaurant, Hatfield. 6.15 p.m.

Preston.—Annual General Meeting and Film Show. "Powered Flight—The Story of the Century" and "Rig 20." R.A.F.A. Concert Hall, Preston. 7.30 p.m.

April 15th

Gloucester and Cheltenham.—Annual General Meeting. St. Mary's College, Cheltenham. 7.30 p.m.

April 23rd

Hatfield.—Annual Dinner. de Havilland Restaurant, Hatfield. 6.15 p.m.

April 28th

Coventry.—Annual General Meeting and Films. Wine Lodge, Coventry. 7.30 p.m.

Southampton.—Some Recent Developments in Civil Engineering. Dr. A. G. Pugsley. Institute of Education, University of Southampton. 7 p.m.

April 30th

Birmingham.—Aircraft Electrics. R. H. Woodall and J. H. Rea. Birmingham Chamber of Commerce, New Street, Birmingham. 7.30 p.m.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Ronald Arthur Allix
Archibald Arthur Avenell
Sydney Buck (*from Graduate*)
Kenneth John Coleman (*from Graduate*)
James Cecil Coombes (*from Associate*)
John Lewis Cutler (*from Graduate*)
Roderick Douglas Dale (*from Graduate*)
William War Daulman
Leslie Arthur Goodson
Percival Stanley Hall
John Owen Isaacs (*from Associate*)
Leonard Cecil James (*from Associate*)
Oscar Philip Jones
Ved Kumar (*from Associate*)
Percy William Lambell (*from Associate*)
Reginald Arthur Langley (*from Graduate*)
Errol Horace Law
Rene Herbert Le Clare (*from Graduate*)
William George Lisle
Peter Ronald McFarlane (*from Graduate*)
Kenneth Joseph McKay
Peter Martin
Philip Arthur Maw
Robert William Molyneux (*from Associate*)
David John Perry (*from Graduate*)
Benjamin Joseph Prior (*from Graduate*)
Henry George Anthony Scilley (*from Associate*)
William John Trotman (*from Graduate*)
Alan James Troughton (*from Graduate*)
Raymond George Welcomme (*from Graduate*)
Aubrey John Roderick Wintle
James Winward (*from Associate*)
Jack Woodhouse (*from Associate*)

Associates

Samuel Berke
Beresford Briggs
Gordon Francis Gartshore Brown
Kenneth Alfred Brownjohn
William Arthur Cook
John David Evans
John Elliott Fox
Gerald Nelson Moore Gingell
Leslie John Hakes (*from Student*)
Ralph Crowther Jones
Thomas Timothy Mehigan (*from Student*)
Trimbak Totaram Naik
Peter William Pedrick
Aubrey Raymond James Preece
Edgar James Roach
Alan Charles Keith Robertson (*from Companion*)
Owen Glyn Seymour
Robert Sharpe
Richard William Raymond Shepard
Clifford Harry Twyman
Michael Cecil Wilson
Edward Donald Wynn

Graduates

Jack Wallace Barker
Frank Russell Beach (*from Student*)
Thomas Shelley Beddoes (*from Student*)
Nigel Kenneth Benson (*from Student*)
Norman Bever (*from Student*)
Brian Leonard Clarkson
David Pierce Comley (*from Student*)
Jeremy Patrick Bourne Cuffe (*from Student*)
Edward Derek Dixon (*from Student*)
Jervois Campbell Firmin (*from Student*)
Desmond Peter Howlett
John Keith Hunt (*from Student*)
Frank Edward Jarlett
Jean Marie Antoine Joseph Jehin (*from Student*)
Alan Lee Johnson
Kenneth Gerald Lane (*from Student*)
Tony Marsden-Jones (*from Student*)
Richard Henry Mathews
David Anthony Rhys Matthews
John Edward Nethaway
Thomas William Nicholls (*from Student*)
Douglas Hector Norrie
John Graham Price (*from Student*)
James Snowdon Roper
Peter Trevor Ryans
Gerald Michael Sacks
Paul Simpson (*from Student*)
John Stafford
Darrol Stinton (*from Student*)
Thomas Thornton
James Walter Useller
Kenneth Ward
John Graham Whitaker

Students

Derek Allan Chandler
Gilbert Frazer Churchill
Walter Stanley Clayton
Gerald Charles Cole
Malcolm Anthony Coote
John Hedley Davies
Eric Dobson
Alan Morley Duxbury
Robin Alexander East
Clive Ellam
John Walter Gardner
Roy Alan Green
Leslie Quinn Hawe
John Bryan Hooton
Simon McNab Humphry
Jonathan Edward Hutchinson
Michael John Hutton
Derek Iredale
Thomas Chuen Lee
Eric Lockton
John Marshall
Raman Muraleedharan Nair
Demetrius Philippou
Lawrence Hodgkins Roberts
John Lister Robinson
Peter Leonard Ruthen
William Herbert Ruthven
Lawrence Shavick
George Alfred Sheppard
Sant Bir Singh Sidana
Norman Cyril Simmons
Alan Ernest Stevens
Edward Gunston Tattersall
Ivan Keith Trundley
James Walton
Peter Waring
William Cecil Wood
Alan Graham Woods

Companions

Frank George Allen
John Fullerton Evetts
Eric John Furlong
Ivan Geoffrey Kasper

Conference on Hydraulic Mechanisms

The Hydraulics Group of the Institution of Mechanical Engineers has invited members of the Society who are interested to a conference on Hydraulic Mechanisms at Storey's Gate, S.W.1, on Friday 26th March. The conference is concerned with modern developments in positive displacement machinery using oil as a medium and contributions to the discussion are invited on topics within this field; servo mechanisms as such are excluded from the scope of the conference. There will be three main sessions between 10.30 a.m. and 7.30 p.m. and luncheon will be available at a nominal charge.

Admission is by ticket only and as accommodation is limited early applications for tickets should be made to the Secretary of the Society.

Instrument Approach (February Journal)—A Correction

It is regretted that on page 207 of the February Journal, Mr. N. E. Rowe was misquoted in the Discussion on Mr. J. F. W. Mercer's paper "A Quantitative Study of Instrument Approach." The first four lines of the second paragraph of Mr. Rowe's spoken comments *should* read:—

"It would be an interesting exercise in economics to decide whether some apparent loss of performance would not in fact be a gain, because it would provide an aircraft which . . ." *instead of*

"It would be an interesting exercise in economics whether some loss of performance, which might be reflected by the very much heavier characteristics on the approach, would provide an aircraft which . . ."

Annual Subscriptions

Members are reminded that their annual subscriptions became due on 1st January 1954. The rates are:—

	Home			Abroad		
	£	s.	d.	£	s.	d.
Fellows	5	5	0	4	4	0
Associate Fellows	4	4	0	3	3	0
*Associates	3	3	0	3	3	0
Graduates (aged under 26)	2	2	0	2	2	0
Graduates (aged 26 and over)	2	12	6	2	12	6
Students (aged under 21)	1	1	0	1	1	0
Students (aged 21 and over)	1	11	6	1	11	6
Companions	3	3	0	3	3	0
Founder Members	2	2	0	2	2	0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the Journal, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 58 MARCH 1954 NUMBER 518

Flight Simulators

by

G. B. RINGHAM, M.Brit.I.R.E., Senior M.I.R.E., and A. E. CUTLER, B.Sc., Ph.D.

(*Redifon Limited*)

The 893rd Lecture to be given before the Royal Aeronautical Society was held under the auspices of the Belfast Branch on 10th December 1953. Rear Admiral M. S. Slattery, C.B., President of the Belfast Branch, presided, and welcomed the visitors. He expressed the regrets of the Branch that the President of the Society, Sir William Farren, C.B., M.B.E., M.A., F.R.S., F.R.Ae.S., was unable to be present, but welcomed the Secretary, Dr. A. M. Ballantyne.

The Branch President, introducing the lecturers, said:—Mr. Ringham is the Manager and Chief Engineer of the Flight Similator Division of Redifon Ltd. He has been connected with the design and development of communication and electronic equipment for over 25 years. He joined Rediffusion (now Redifon Ltd.) in 1939, and worked extensively on the development of navigational training aids during the war years.

His co-lecturer is Dr. Cutler, Chief Designer of the Flight Simulator Division of Redifon Ltd. He worked on naval navigational aids with the Admiralty Signal Establishment during the war, returning to the development laboratories in Haslemere at the close of the war in Europe. He re-entered Nottingham University later and obtained his B.Sc., Special Physics, and then did research work and was granted his Ph.D. in 1952.

Following the Lecture Rear Admiral Slattery said that it was the practice in the Belfast Branch to present a small memento to lecturers who did them the honour of coming to Belfast and he had much pleasure in presenting the lecturers with a small memento each of Irish linen.

The Lecturers presented their paper and then showed a film depicting sections of a simulated flight from Rome to London.

1. Flight Simulators

The hazards of flying, the skill required to pilot aeroplanes and the often complicated nature of the flying machine, have created the need, from the earliest days, for safe non-airborne training aids for pilot and air crew instruction. Attempts to meet the problem have ranged from machines with sawn off wings pivoted to balance in the breeze, to the more complicated navigational training devices developed and brought into use in this country from the year 1939 onwards.

The earliest devices appear to have been devised around 1910, using actual aircraft moving at speed and supported by balloons, overhead gantries and railway bogies.

About the same time an apparatus adaptable to suit individual control layouts was described in which the instructor produced misalignment of a pivoted fuselage on one set of controls, while the pilot made corrections on a second set, excessive angular movements causing a warning bell to be operated. Another proposal due to Sanders was essentially an aircraft mounted on a universal joint facing into the wind as in Fig. 1[1].

An equipment based on a pivoted fuselage, using compressed air and producing variations of response and feel with assumed speed, was produced in France in 1917[2]. No instrumentation was provided. Engine noise, rudder/aileron crossover and rudimentary visual approach were included. In the next year a development of this device appeared in which the induced air flow from a propeller mounted as in the aircraft, was used to produce tilting of the fuselage in response to elevators, rudders and ailerons. The instructor introduced disturbance through a second set of control surfaces.

Systems along the same general lines were also put forward in Great Britain, Canada, America and Germany, during the years 1918-1931.

In 1931 the first instrument flying trainer was described, which included an A.S.I. responsive to pitch and throttle, bank needle responsive to aileron and a turn indicator responsive to rudder. Heading was determined by an integrator device associated with rudder, therefore integrating the indicated rate of turn. The throttle also operated a tachometer and influenced the rate of climb. Dashpots were suggested to produce damping of the response to controls. The instructor set in problems on a second set of controls[3].

From this time onwards many ideas were put forward for improving instrumentation including northerly turning error, compass acceleration error and pitch

manometer acceleration error. Glide path indicators and morse keying devices were also included in training apparatus.

In 1929, in Germany, Roeder[4] described an apparatus for instruction in the navigation of vehicles in free space, with particular reference to aircraft, airships and submarines. This remarkable description contained a diagram (Fig. 2) which, it will be seen, anticipates the computing method of the modern fixed base flight simulator. A hydraulic mechanism for producing physical movements of an airship monocoque, not unlike the pneumatic control system used on some modern trainers was also shown.

In 1936, mainly due to the work of Edwin Link in the U.S.A., the flying trainer moved rapidly towards the form in which we know it today. The "crab" plotting table, A.N. range and radio beacons, were added to the instruments included in the earlier trainers to give a comprehensive instrument trainer, the radio facilities being introduced by the instructor as appropriate.

The 1939-45 War gave great impetus to the development of devices for training in the flight and effective operation of military aircraft with particular emphasis in the use of radio and radar navigational aids. The pioneer work of Adorian and his associates in 1940 in the firm which now makes Redifon flight simulators was followed by contributions from a large number of others.

During 1941-42, as the aircraft in use became more complicated, the trainers were extended in scope to cover new requirements, the individual elements of the system being treated more thoroughly. Examples of these are the operation of the ball-bank indicator, effects of stall on altitude, the introduction of drags due to attitude as produced by elevator and rudder, the introduction of manifold pressure gauges responsive to throttle and altitude and many others.

The Telecommunication Research Establishment (Ministry of Supply) were responsible for a large part of the development of trainers for service use during the war and a description of some navigation, interception and blind bombing devices produced there was later given by Dummer[5].

The production of effects by electrical means was devised around this time by Dehmel in the U.S.A. and later by Winstanley in Great Britain.

Radio aids training possible at the time included A.N ranges, direction finding, radio compass, automatic D.F. and glide path.

Trainers were progressively improved through the war years, particularly in aerobatic performance, but never overcame the disadvantages of lacking realistic attitude response.

Hellings appears to be the first person to describe in some detail an application of electrical methods to the solution of equations for flight trainers. He described the solution of simultaneous differential equations for lift and drag equilibrium to determine air speed and pitch angle. Extension of the lift and drag terms was envisaged to include many second order effects. The modern flight simulator however, is based on a different and more general method than that given above.

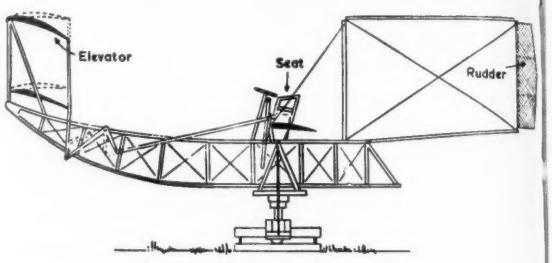

FIGURE 1. The Sanders teacher.

The development of gunsight and bombing radar opened a new field of possibilities which was quickly exploited, particularly in the U.S.A.

Link in 1945 described a new form of trainer based upon the use of inter-related pneumatic circuits to give closer approximation to the solution of flight problems, a parallel development to the electrical methods of Curtiss Wright which in 1945 led to the 400 type trainer. Both companies introduced variable control loading into their trainers at about this time.

The trainers which have so far been mentioned have all been general types intended principally for basic training. They have over the past 30 years or so given, and are continuing to give, excellent and efficient service in primary and refresher training, but at no time has there been any possibility of using them to reduce air flying time. Instruction, particularly on instrument approaches has been a valuable adjunct to actual flying and this is still a very important feature of all flying trainers. The great dissimilarity, both in appearance and behaviour, between them and the aircraft has however restricted their use for other purposes. A great need therefore existed for a device which could hope to reduce substantially the flying time necessary for conversion and instrument training. Such a device in order to embody conversion as a substantiated part of total training must be an exact replica of the aircraft and so similar in all aspects of performance that the student pilot believes that he is in the actual aircraft.

The introduction by Curtiss-Wright of a generalised technique of computing soon resulted in an order from Pan American Airways to Curtiss-Wright to produce such a trainer, specifically to represent the Boeing Stratocruiser, reproducing all the aerodynamic, engine and handling performance and furnishings in facsimile. This very bold move on the part of Pan American Airways and Curtiss-Wright resulted in a flight simulator in November 1948, and it was such a complete success that soon Pan American were able to give an estimated figure of 60 per cent. saving on training costs[6].

This precedent was very rapidly followed by the U.S. Navy and Army Air Forces, the Ministry of Supply, B.O.A.C., B.E.A., Eastern Airways, Trans-World Airways and many others, and many orders for flight simulators were placed.

The degree of complexity and therefore the cost of a flight simulator, is great and with this in mind orders were simultaneously placed for a number of devices often confused with flight simulators, called "flight duplicators." The flight duplicator is a generalised

flight trainer which has been modified somewhat to have an instrument and control disposition representative of a particular aircraft, no great effort being made to match the operating performance. In passing it should be noted that the name "flight simulator" is often indiscriminately used in Great Britain to indicate any form of missile, flutter, stability or aerodynamic computer in addition to the sense in which it is interpreted in this paper.

Flight simulators for the Stratocruiser and Comet aircraft are being used by the B.O.A.C. in this country, and a large number of diverse types have been produced in America. In both countries numbers of new simulators are under construction.

In its present form the flight simulator is a teaching instrument working upon well-known electro-mechanical and electronic principles in which both normal and emergency flight conditions are fed in, to pose problems for which the trainees must find the correct answers in their handling technique. If they fail, they can be shown their faults and the cure, while still remaining in friendly and safe contact with the ground and using no aircraft flying hours. The aim is to reduce to the minimum the process of flight familiarisation with its attendant potential hazards and high cost, while the ability to confront the trainee crew with abnormal contingencies prepares them for any emergency they may have to face. During any expansion programme on a new type of aircraft there is a powerful case for the development of such ground training equipment in parallel with the prototype aircraft to reduce the cost of initial training.

In the Services, where there is continuous turnover of personnel, the flight simulator can be used for conversion training throughout the whole of the life of the aeroplane and hence has even greater economic potentialities.

Almost any navigational problem and emergency condition within reason can be fed into the instruments and controls during an exercise. The reaction of the crew to such emergencies and their methods of solving the problems are carefully noted and corrected by the instructor and check pilot. The result is that on completion of the course the crew can approach an actual aircraft with full confidence, being thoroughly familiar with the positioning, the handling and the sensing of the controls and instruments. Engine and instrument failures are examples of emergencies which can be introduced. The course starts with a complete briefing after which the crew take their position in the simulator exactly as in the actual aircraft, perform starting drills and check list procedures, taxy out and take-off.

All the conditions found in flight can be found in the simulator with the exception of the physical effect of accelerations. The absence of this effect may be thought a disadvantage until it is realised that skilled crews no longer fly "by the seat of their pants"—training for the modern aeroplane demands something more than was thought sufficient in the old days. The forces experienced

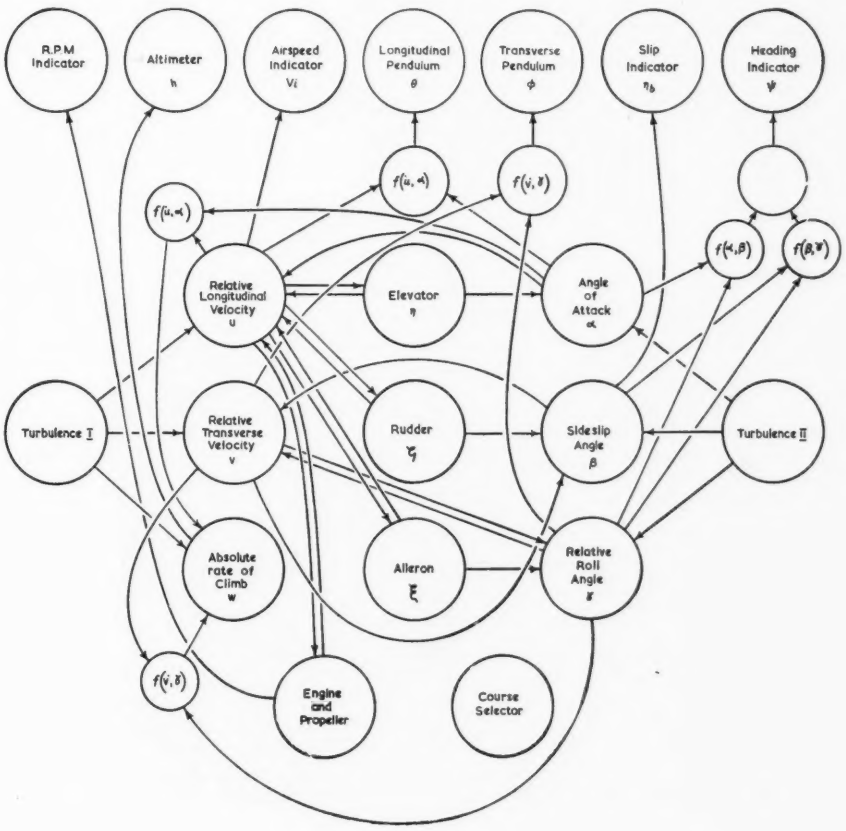

FIGURE 2. Flight computer suggested by Roeder.

TABLE I

ESTIMATED HOURLY OPERATING COSTS INCLUDING DEPRECIATION FOUR-ENGINED AIRCRAFT

	Comet III	*Typical Piston-engined Aircraft*
Direct operating cost	£ per aircraft flying hour	£ per aircraft flying hour
Obsolescence	44·4	33·0
Maintenance and overhaul	60·4	59·7
Fuel and Oil, Landing Fees	96·7	55·8
	201·5	148·5

and necessarily exerted by the crew at the controls are accurately representative of those in the actual aircraft and with aural effects and realistic instrument presentation, efficient and economic crew conversion is assured.

In addition to crew familiarisation and conversion, six monthly checks can be carried out by Captain, First Officer and Flight Engineer, and because of the low operational cost many more hours can be devoted to this instruction.

Figure 3 shows a flight simulator as it might well be arranged for such training, indicating a suitable disposition of fuselage, computers, instructor's office and briefing room. Fig. 4 shows the flight deck of the Comet simulator.

2. The Economics of Flight Simulators

The great complexity of the modern transport or military aeroplane makes it not only expensive to buy but costly to fly and maintain. Because of this the modern aircraft operator cannot afford to keep aircraft permanently out of service for training purposes; the sums of money involved are enormous. The flight simulator therefore comes as a blessing to civilian and service operators alike.

TABLE II

ESTIMATED HOURLY OPERATING COSTS EXCLUDING DEPRECIATION FLIGHT SIMULATOR

	£ per hour
Maintenance and overhaul	1·75
Power and heating	0·45
Radio Aids Instructor (ground facilities)	0·5
	2·7

An appreciation of the great savings which may be effected using a flight simulator can best be obtained by an examination of the operating costs of a typical modern four-jet airliner, in this case the Comet III, and the equivalent flight simulator. The figures shown in Table I are obtained from the *de Havilland Gazette*[7] and are clearly estimated only The passenger revenue of this type is of course unknown. The crew members' salaries have been subtracted to line up with the simulator table.

It is not intended here to make a comparison of the two types of aircraft. De Havilland demonstrate[7] that the higher work capacity of a jet aircraft favourably offsets the higher operating cost.

For comparison, Table II shows the estimated hourly cost of operating a flight simulator. It is noteworthy that an aircraft has an expected flying life of say 25,000 hours. A simulator is good for at least 75,000 hours. by which time it will be too old anyway.

Combining the above figure with depreciation at a rate determined by usage, gives

$$\text{Hourly cost} = \text{direct hourly cost} + + \frac{\text{first cost}}{\text{total hours of use}}.$$

This relation is plotted for a first cost of £160,000 (including building, accommodation and installation) with utilisations from 500-4,000 hours a year over 3, 5, 7 and 10 years in Fig. 5.

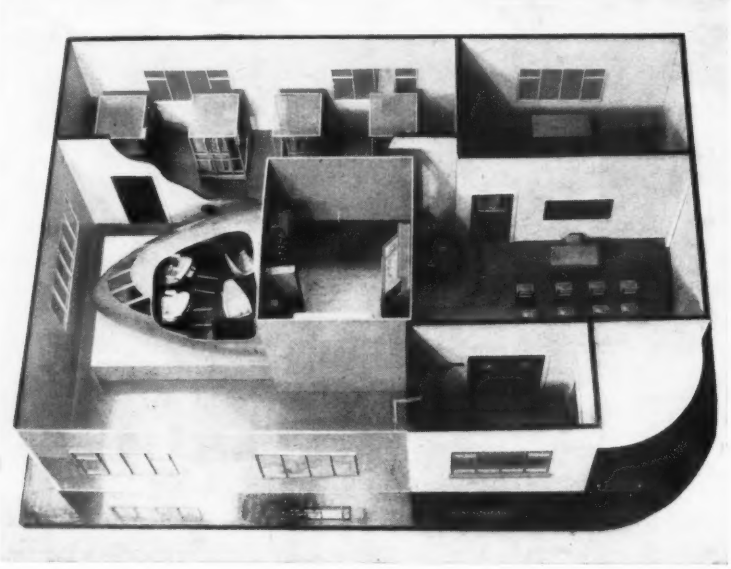

FIGURE 3. Comet building.

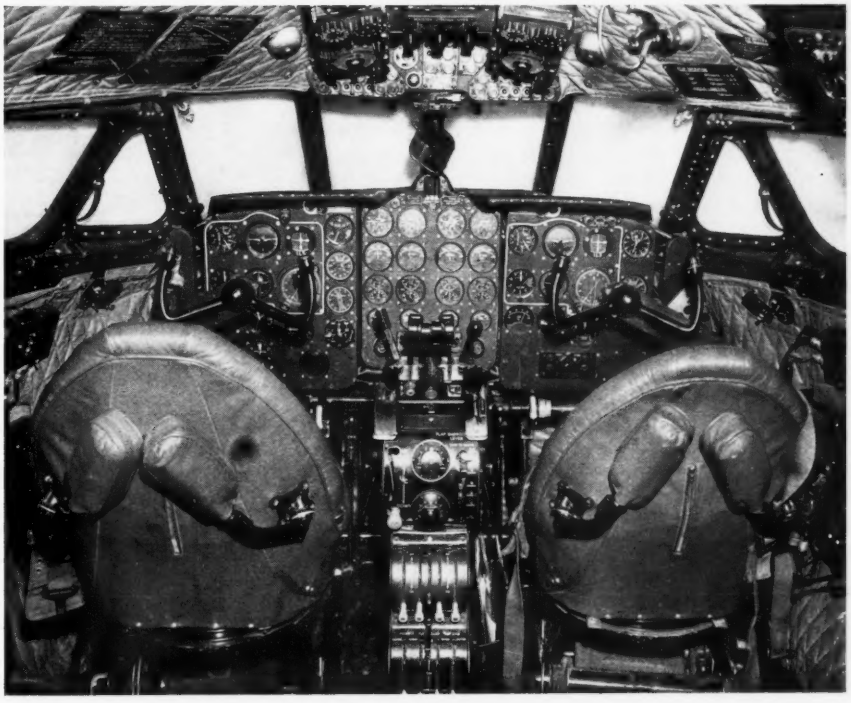

FIGURE 4. Comet flight deck.

These figures correspond fairly well with the figures published by Wood in 1952[8] here shown in Table III and an estimate by Klass[9] of $30 per hour for a simulator and $350 for the DC-6 or Constellation aircraft. Loss of passenger revenue is not included in these estimates.

Scott-Flower[10] gave a five-year life figure of $67.5 per hour (approximately $48 on a 10-year basis).

Further emphasis on the economies which may be effected is given by the utilisation figures possible with flight simulators, which range from 10-15 hours per day; 20 hours per day has been attained for a short period.

After an initial shakedown period of a few months, the loss of training time due to unserviceability of the equipment is in all the foregoing cases, less than 2 per cent.

3. Comparative Training Times

It is not possible to define any relation between simulator time and flying time saved in the general case. An operator with a flight simulator and only a few aircraft will naturally make the best possible use of his simulator by allocating as many hours as possible to training. It can never be stressed too much that the constant repetition, without risk, of normal and emergency procedures and drills produces a quiet confidence in the crew that they can cope as adequately as is possible with any real emergency. Knowledge of the proper drills makes them speedy and efficient and they work better together. There is time also in a simulator to go back repeatedly over each section of the drill to ensure that it is being performed in the best possible way. A simple example of this appeared in approach training on the P.A.A. Stratocruiser simulator, when to correct undershooting of the glide path the pilot called "Take-off power." The engineer pulled back all throttles and the simulator "crashed." The drill was changed to include the expression "full power."

The standard flight simulator training periods for conversion courses are given in Table IV. The total

TABLE III

COMPARISON OF AIRCRAFT AND SIMULATOR COSTS

Type	*Direct Operating Costs $ per hour*
B-36	1024
B-50	421
F-86	145
B-17	97
Simulator	10·8

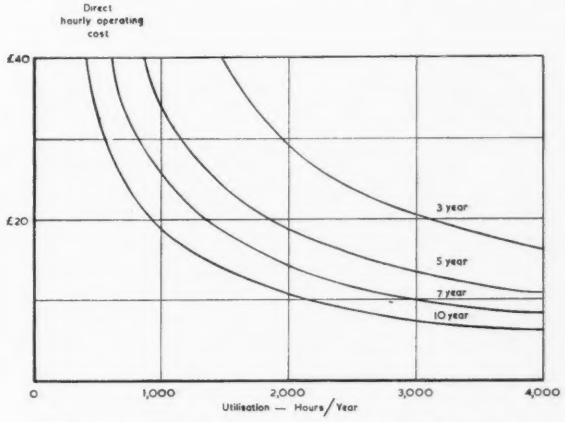

FIGURE 5. Hourly operating cost of a flight simulator including depreciation.

time allocated is 35 hours compared with the usual figure of 20 or so in the aircraft, thus greatly increased familiarisation is obtained at a fraction of the operating costs. A few hours of aircraft flying are needed to cover those aspects of flight which are not intended to be fully practised in the simulator, such as "circuits and bumps," and to confirm the knowledge gained by the pilot on the simulator.

B.O.A.C.'s Stratocruiser and Comet simulators have been approved by the Ministry of Civil Aviation for use, hour by hour, in six month checks and in many circles it is felt that as experience is gained in training with the flight simulators at present under construction, more than ever of the training may be performed on them.

TABLE IV

Crew	*Pilot Station*	*Engineer Station*
Captain	15	2·5
First Officer	15	2·5
Flight Engineer—concurrent	30	5·0
		30·0
Total Simulator Time		35 hours

Notation

COMPUTING ELEMENTS (Section 4)

x, y	voltages representing co-ordinates
θ, θ'	angles representing heading
δ	servo error angle

FLIGHT (Section 5.1)

m, W, T	mass, weight and thrust
x, y, z	aircraft principal axes (forward, sideways and downwards)
A, B, C, D, E, F	moments and products of inertia about the aircraft principal axes
X, Y, Z	aerodynamic forces along the aircraft principal axes
X', Y', Z'	forces along the aircraft principal axes including gravitational effects
C_D, C_C, C_L	force coefficients (subscripts . . . 0 and . . . F indicate profile and flap effects)
L, M, N	moments about the aircraft principal axes
C_l, C_m, C_n	moment coefficients
ξ, η, ζ	aileron, elevator and rudder deflections
α, β, γ	angles of incidence, sideslip and relative roll
α_t, ε	tail incidence and downwash at tail
u, v, w	velocity components along the aircraft principal axes
V_T, V_i	true and indicated values of resultant air speed
c	velocity of sound at 15°C.
Mn	Mach number
q	dynamic air pressure $=\frac{1}{2}\rho V_T^2$
p, q, r	angular velocity components about the aircraft principal axes
ϕ, θ, ψ	aircraft roll, pitch and heading angles
η_b	slip indicator ball angle
S, b, c	wing area, span and mean chord
$\overline{V}, l$	tail volume and reference length
A_1, A_2	tail and elevator efficiencies

AERODYNAMIC DERIVATIVES

$$l_\xi = \frac{\partial C_l}{\partial \xi}\ ;\quad l_\zeta = \frac{\partial C_l}{\partial \zeta}\ l_v = \frac{\partial C_l}{\partial \beta}\ ;\quad l_p = \frac{\partial C_l}{\partial\left(\frac{pb}{2V_T}\right)}\ ;$$

$$l_r = \frac{\partial C_l}{\partial\left(\frac{rb}{2V_T}\right)}$$

$$m_q = \frac{\partial C_m}{\partial\left(\frac{ql}{V_T}\right)}\ ;\quad \mu_1 m_{\dot{w}} = \frac{\partial C_m}{\partial\left(\frac{\dot{\alpha} l}{V_T}\right)}$$

$$n_\xi = \frac{\partial C_n}{\partial \xi}\ ;\ n_\zeta = \frac{\partial C_n}{\partial \zeta}\ ;\ n_v = \frac{\partial C_n}{\partial \beta}\ ;\ n_p = \frac{\partial C_n}{\partial\left(\frac{pb}{2V_T}\right)}\ ;$$

$$n_r = \frac{\partial C_n}{\partial\left(\frac{rb}{2V_T}\right)}$$

ATMOSPHERE

h, H	altitudes above sea level and ground
t, t_0, t'	ambient and sea level temperatures; temperature given by extrapolating linear lapse through tropopause
p, p_0	ambient and sea level pressures
ρ	air density

4. Computing Elements

Complete simulation of a modern aeroplane requires a very extensive knowledge of the aeroplane itself, for in addition to the flight, engine and atmospheric data, it is necessary to have complete circuits for all the electrical services and instruments fitted in the flight deck, operating details of hydraulics, auto-pilots, undercarriage systems, cabin pressurisation and all radio facilities.

The form of computing is related to the operational data supplied by the manufacturers, only the basic flight, cabin pressurisation and radio aids systems being common to all aircraft. Other systems vary so greatly from aircraft to aircraft that a specific approach governed only by the broad principles of analogue computing technique is necessary for each particular item.

Although digital computers have been discussed extensively in connection with flight simulators, as far as is known only the U.S. Navy has made any attempt to use them. The analogue type is normally preferred because it operates in real time, *i.e.* the processes used in the computing occur at the same rate as the processes which they represent in the particular aeroplane they simulate.

There are many variations in basic analogue computing technique and several authors[11, 12] have attempted to assess their relative importance. Broadly speaking, one can say that if any one technique had outstanding advantages it would have been used exclusively by all manufacturers. As this is not so, it must be concluded that, although there may be relative advantages and disadvantages, these are not so great as to outweigh the confidence which engineers have in the handling of the technique to which they are accustomed.

The following comments are not exhaustive but serve to indicate the general line taken by the industry.

BASIC POWER

Although Link have produced a computing mechanism based on pneumatic principles, all known flight simulators for air crew training are electrically operated.

CHOICE OF CARRIER

The "carrier" is that quantity which is used for transmission of information in the computers and may be A.C. or D.C. voltage or current, phase shift in an A.C. wave form, or pulse length in interrupted D.C. Of these the most favoured are A.C. and D.C. voltages because they may readily be added, amplified and resolved or used to operate instruments and servo devices.

For close tolerance computing the stability of output of A.C. amplifiers under wide variations of valve and circuit parameters and their absolute freedom from drift makes the A.C. carrier essential. It is necessary to maintain a good standard of wiring layout to reduce crosstalk and also to provide efficient filtering of H.T. supplies, although these are no more than is required for any complicated electronic device. The crosstalk normally consists of harmless harmonics in very small quantities and the objections to its presence are more aesthetic than operational. A penalty which must be paid is the comparatively low efficiency of the A.C. induction motor but even this is offset because, having no brush gear, the starting friction of this motor is very low. The low mechanical loading of a typical computing equipment makes the starting power well within the limits of a small single ended valve amplifier (less than one watt).

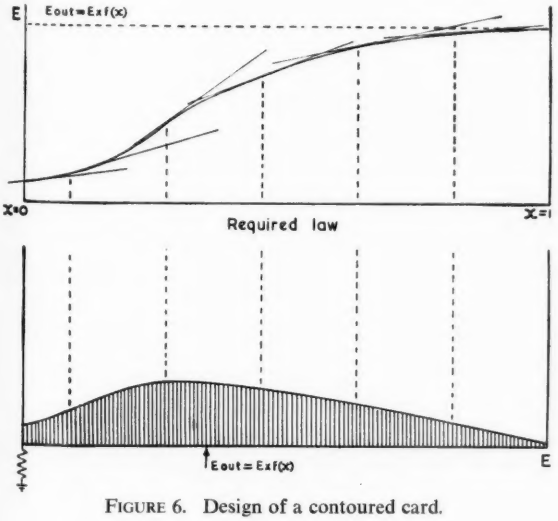

FIGURE 6. Design of a contoured card.

MATHEMATICAL OPERATIONS

The operations which it is necessary to perform on the carrier in the course of the computing are addition and of course subtraction, multiplication, function generation, integration and resolution.

ADDITION

Addition is readily performed either by series addition, for which the method is obvious, or parallel addition in input networks, the value of each resistor carrying the e.m.f. to a common point being determined by the required effect of each voltage in the sum. Subtraction is obtained normally by reversal of the polarity of one of the voltages.

MULTIPLICATION

The method of multiplication is determined largely by the method of integration. If the integration is produced by an electro-mechanical method, it is normal to follow suit with position-operated devices for multiplication, the mechanical process involved being used to move the brushes on potentiometers fed with one of the voltages, the brush position being controlled by the other voltage or its integral to give a product. These electro-mechanical devices are frequently called "computing servos." This is without doubt the easiest and most accurate of the methods available but is rather expensive; most of the other methods rely on the grid characteristics of valves in some respect and therefore are neither greatly accurate nor very stable over long periods.

Good accuracy is possible by application of pulse technique and this could be considered as a possible solution to the accuracy problem if a non-mechanical integrator of high stability were available.

FUNCTION GENERATION

Referring again to the electro-mechanical method it is clear that any method for changing the law of a potentiometer such as contouring, shunting or tapping is possible as a general solution to all function generating problems.

In the design of a contoured potentiometer (Fig. 6) the width contour is determined by the slope of the desired function with appropriate allowance being made for the effects of load.

With a non-mechanical system the normal methods require the use of trick circuits for a limited number of simple functions or, for a general technique, the use of rectifier and resistance meshes.

All these methods rely on curve fitting or straight line approximations except the contoured potentiometer, which may be constructed to give any function to any accuracy, although better than $\frac{1}{4}$ per cent. is seldom attempted.

INTEGRATION

In A.C. electro-mechanical computers the normal integrator is an amplifier and motor-generator combination normally called a velodyne, a device so arranged that the difference between the generator produced rate voltage and the driving voltage is used as the input of the high gain amplifier driving the motor as in Fig. 7.

When no further acceleration takes place, a condition which is rapidly reached because of the low system inertia, the speed of the motor is proportional to the input voltage and this is true over a wide speed range. Operating in real time, the rotation as viewed at the end of a reduction gearbox represents the time integral of the speed and hence of the input function.

A similar function is automatically carried out by any armature controlled D.C. motor, except that the brush gear makes operation at low speeds somewhat erratic.

The best known non-mechanical integrator is the Miller type electronic integrator in which the charging of a condenser through a high resistance, itself a form of integration, is modified by an associated amplifier effectively to multiply the capacity of the condenser by the gain of the amplifier. The leakage across ordinary condensers through the dielectric causes drift which, at large values of the integral of the input variable, can be very serious and for long term accuracy and stability drift compensators or special plastic film dielectric condensers must be used. A further disadvantage of the electronic integrator is that it automatically reverts to zero when the power is removed, making it impossible to "store" a situation. It is however very cheap and completely satisfactory for high-speed operation.

RESOLUTION

The contoured potentiometer card can readily be employed to generate normal trigonometrical functions of a variable but special techniques are necessary for the solution of equations involving inverse trigonometrical functions, *e.g.* $\theta = \tan^{-1} x/y$ where θ is the unknown, x and y being known variables. If θ' is a trial solution and δ is the error on this solution then

$$\sqrt{(x^2+y^2)} \sin\delta = x\cos\theta' - y\sin\theta'.$$

A mechanism is therefore constructed to give an output of the form $(x\cos\theta' - y\sin\theta')$ which is fed back to the input in such a way that the mechanism then moves to reduce the output to zero. When $\sin\delta = 0$, $\tan\theta' = x/y = \tan\theta$, the required solution.

In A.C. computers a two-phase resolver can very conveniently be used in conjunction with a servo to produce this result although potentiometers may also be used. Such a mechanism is used in the A.D.F. system shown later. An advantage of the resolver is that in a transverse winding to that which naturally produces $\sqrt{(x^2+y^2)}\sin\delta$ from x and y fields there is induced a voltage $\sqrt{(x^2+y^2)}\cos\delta = x\sin\theta'$ which, when $\sin\delta = 0$, gives $\sqrt{(x^2+y^2)}$, the distance from the origin of co-ordinates to the point x, y, a quantity which is frequently required. Using potentiometers this quantity is obtained by separate brushes on the potentiometers

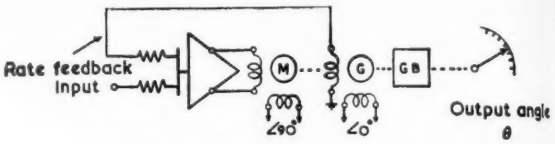

FIGURE 7. Integrator mechanism.

normally used for generating $x\cos\theta'$ and $-y\sin\theta'$ which are arranged to produce $x\sin\theta'$ and $y\cos\theta'$.

The process involving resolution requires a high order of accuracy and hence there is usually no adequate alternative.

From these notes on mathematical processes it is evident that greater accuracy and stability may be obtained by using A.C. techniques than is possible by D.C. The complex and exacting requirements of a modern flight simulator therefore compel the use of A.C., the D.C. methods being more useful in general trainers and the lower accuracy flight duplicators.

5. Principle of Operation

5.1. FLIGHT

For the simulation of the flight of an aircraft, the aircraft designers must supply to the simulator manufacturers the values of all the stability coefficients and their variation with Mach number and changes in aircraft geometry as produced for example by flaps, undercarriage and dive brakes. For propeller-driven aircraft there are also effects due to induced air flow over the wings and tail. The control gearings and considerable quantities of other geometrical data are also required.

The supply of complete and accurate data is a fundamental requirement of flight simulators. In the case of a new aircraft, the delivery of the simulator is required several months ahead of the production aircraft because during the conversion programme the greatest economies are made. The aerodynamic data must therefore be estimated before the flight of the first production aircraft and confirmed before delivery of the aircraft to the customer.

From the aerodynamic data the best of variables is decided upon. This is a relatively simple process since the specification of stability data is now fairly standard, although certain of the effects may still be given, for example as functions either of angle of incidence or lift coefficient.

The aerodynamic performance is determined by forces X, Y, Z, and L, M, N, defined in the normal way and the computer must first evaluate these from equations similar to the following:—

Forward force

$$X = T - \tfrac{1}{2}\rho V_T^2 S \left\{ C_{D_0} + kC_L^2 + C_{D_F} + \text{effects of ground, undercarriage, air brakes, bomb doors} \right\}. \quad . \quad . \quad . \quad . \quad (1a)$$

Side force

$$Y = \tfrac{1}{2}\rho V_T^2 S \left\{ \frac{\partial C_0}{\partial \zeta}\zeta + \left[\frac{\partial C_c}{\partial \beta} + \text{effects of ground, undercarriage, air brakes, bomb doors} \right] . \beta \right\} \quad (1b)$$

Lift

$$Z = -\tfrac{1}{2}\rho V_T^2 S \left\{ C_L(\alpha) + C_{L_F} + \text{effects of ground, undercarriage, air brakes, bomb doors} \right\} \quad (1c)$$

Rolling moment

$$L = \tfrac{1}{2}\rho V_T^2 Sb \left\{ l_\xi \xi + l_\zeta \zeta + l_v \beta + l_r \left(\frac{rb}{2V_T}\right) + l_p \left(\frac{pb}{2V_T}\right) + \text{effect of thrust and incidence} \right\} \quad (2a)$$

Pitching moment

$$M = \tfrac{1}{2}\rho V_T^2 Sc \left\{ C_m(\alpha) - \bar{V}\left[A_1(\alpha - \varepsilon + \alpha_t) + A_2\eta\right] + \frac{2l}{c}\left[m_q \left(\frac{ql}{V_T}\right) + \mu_1 m_{\dot{w}} \left(\frac{\dot{z}l}{V_T}\right) \right] + \text{effects of ground, undercarriage, air brakes, bomb doors.} \right\} \quad (2b)$$

Yawing moment

$$N = \tfrac{1}{2}\rho V_T^2 Sb \left\{ n_\xi \xi + n_\zeta \zeta + n_v \beta + n_r \left(\frac{rb}{2V_T}\right) + n_p \left(\frac{pb}{2V_T}\right) + \text{effects of incidence, } n_r \text{ and asymmetrical thrust} \right\} . \quad (2c)$$

Most of the foregoing coefficients and derivatives are modified by Mach number and aeroelastic distortion.

In these equations are embodied the whole stability of the aircraft and the formation of the terms from graphical data comprises the major part of the flight computing.

Having determined the forces and couples, the aircraft can be treated as the proverbial "block of wood" in which are fixed a set of orthogonal axes having their origin at the centre of gravity and pointing forwards, sideways and downwards (relatively).

The standard text books on dynamics show that if the body has mass m and linear velocities u, v and w, and angular velocities p, q and r, along and about the x, y and z axes, and if X', Y', Z' are given by the following relations in which the gravity terms are approximated to obtain the values when the angles of attack and sideslip are both zero,

$$X' = X + \text{resolved gravity component along } x \text{ axis} \quad (3)$$

$$\simeq X - mg\sin\theta \quad (3a)$$

$$Y' = Y + \text{resolved gravity component along } y \text{ axis} \quad (4)$$

$$\simeq Y + mg\cos\theta\sin\phi \quad (4a)$$

$$Z' = Z + \text{resolved gravity component along } z \text{ axis} \quad (5)$$

$$\simeq Z + mg\cos\theta\cos\phi \quad (5a)$$

ϕ and θ are the angles of pitch and roll. Then:

$$\dot{u} = \frac{X'}{m} - wq + vr \quad (6a)$$

$$\dot{v} = \frac{Y'}{m} - ur + wp \quad (6b)$$

$$\dot{w} = \frac{Z'}{m} - vp + uq . \quad (6c)$$

The first term is an expression of Newton's law and the other two the result of changing the directions of the axes along which u, v, w are resolved at the rates p, q, r, while retaining the spatial velocity

$$V_T = \sqrt{(u^2 + v^2 + w^2)}$$

unchanged in magnitude or direction.

The angular accelerations are given by

$$L = h_1 - rh_2 + qh_3 \quad (7a)$$

$$M = h_2 - ph_3 + rh_1 \quad (7b)$$

$$N = h_3 - qh_1 + ph_2 \quad (7c)$$

$$h_1 = pA - qF - rE \quad (8a)$$

$$h_2 = qB - rD - pF \quad (8b)$$

$$h_3 = rC - pE - qD \quad (8c)$$

A, B and C and D, E and F, are the moments and products of inertia about the x, y and z axes.

The terms $\dot{p}A$, $\dot{q}B$, $\dot{r}C$ represent the equivalent of Newton's law in the rotational sense and the other terms express the well known gyro principle that a body with inertia rotating about one axis, if simultaneously rotated about a second axis, will precess about the third.

These equations contain many terms which are neglible or zero. For instance, in a high-speed aeroplane w and v, the transverse velocities are of order less than 5 per cent. of u the forward velocity, except in extreme manoeuvre.

The changes of the linear velocities are obtained by integration of the foregoing expressions which include rates of rotation and since the resultant angular displacements are also obtained by integration of these rates, the net contribution of the rate terms are related to the total angular movements, which are small in large passenger aircraft where extreme manoeuvres are avoided in the interests of comfort.

Modern aircraft have a high degree of symmetry about the z direction in the y, z plane and the x direction in the x, y plane giving $E=0$, and $D=0$ and F is of much smaller order than A, B or C.

A representative set of approximations to the foregoing equations may be written:

$$\dot{V}_T = \dot{u} = \frac{X'}{m} . \quad (9a)$$

$$\dot{v} = \frac{X'}{m} - ru = \frac{Y'}{m} - rV_T \quad (9b)$$

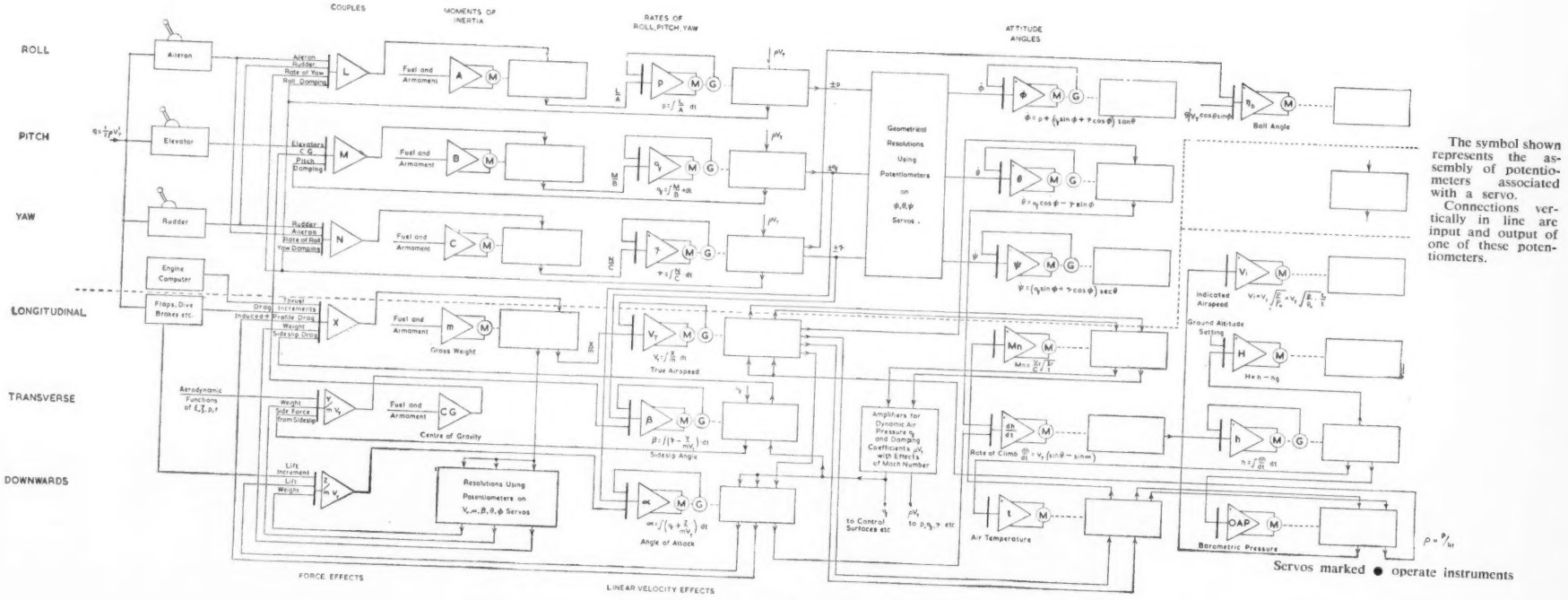

FIGURE 8. Flight computer.

$$\dot{w}=\frac{Z'}{m}+qu=\frac{Z'}{m}+qV_T \quad . \quad . \quad (9c)$$

$$\dot{p}=\frac{L}{A}+\frac{(B-C)}{A}qr \quad . \quad . \quad . \quad (10a)$$

$$\dot{q}=\frac{M}{B}+\frac{(C-A)}{B}rp \quad . \quad . \quad (10b)$$

$$\dot{r}=\frac{N}{C}+\frac{(A-B)}{C}pq. \quad . \quad . \quad (10c)$$

For civil aircraft

$$\dot{p}=\frac{L}{A};\ \dot{q}=\frac{M}{B};\ \dot{r}=\frac{N}{C} \quad . \quad (11a,b,c)$$

are adequate.

Some of these approximations may not appear to be consistent with the general accuracy required in a flight simulator, but it must be remembered that an aircraft is always in dynamic equilibrium such that a given control movement will in general produce a given change in stable attitude ($\dot{u}=\dot{v}=\dot{w}=0$; $p=q=r=0$; $\dot{p}=\dot{q}=\dot{r}=0$). This attitude is determined by the condition that the sum of terms in each of X', Y', Z'; L, M, and N is independently zero. The terms in these, except for damping terms which are reduced to zero in the resulting stable condition, involve only quantities such as attitude, control surface angles, power settings, and air speed. The effect of the approximations is therefore felt only in the response characteristics and in this direction slightly more lattitude is permitted.

The angles of attack and sideslip are defined by

$$\alpha=\tan^{-1}\frac{w}{u}\simeq\frac{w}{V_T} \quad . \quad . \quad . \quad (12a)$$

$$\beta=-\sin^{-1}\frac{v}{V_T}\simeq-\frac{v}{V_T}. \quad . \quad . \quad (12b)$$

Hence from (9c) and (9b)

$$\alpha=\frac{1}{V_T}\int\dot{w}\,dt=\frac{1}{V_T}\int\left(\frac{Z'}{m}+qV_T\right)dt \quad . \quad (13a)$$

$$\beta=\frac{1}{V_T}\int\dot{v}\,dt=\frac{1}{V_T}\int\left(\frac{Y'}{m}-rV_T\right)dt \quad . \quad (13b)$$

approximating to

$$\alpha\simeq\int\left(\frac{Z'}{mV_T}+q\right)dt \quad . \quad . \quad (14a)$$

$$\beta\simeq-\int\left(\frac{Y'}{mV_T}-r\right)dt \quad . \quad . \quad (14b)$$

by assuming that the velocity is constant over a small change in angle of attack.

Integrators as described above are used to evaluate equations for p, q, r, α, β and V_T; these quantities may be described as being at "velocity" level.

In order to obtain the linear and angular displacements, a further set of integrations is necessary.

All displacement data is given with respect to earth axes and it is necessary first to resolve the velocities through the attitude angles of the aeroplanes with respect to the earth and then to integrate to obtain these displacements.

The resolution of angular velocities produces exact forms (15a), (15b), (15c) which can be integrated to give the attitude angles, but in the linear sense the complicated results must be approximated. Forms which may readily be understood are given in equations (16a), (16b), (16c). Those used in the computers are of a more exact nature.

$$\phi=\int p+(q\sin\phi+r\cos\phi)\tan\theta\,dt \quad . \quad (15a)$$

$$\theta=\int(q\cos\phi-r\sin\phi)\,dt \quad . \quad . \quad . \quad (15b)$$

$$\psi=\int(q\sin\phi+r\cos\phi)\sec\theta\,dt \quad . \quad . \quad (15c)$$

$$V_X=V_{E-W}=V\cos\theta\sin\psi \quad . \quad . \quad . \quad (16a)$$

$$V_Y=V_{N-S}=V\cos\theta\cos\psi \quad . \quad . \quad . \quad (16b)$$

$$V_Z=\frac{dh}{dt}=V_T(\sin\theta-\sin\alpha) \quad . \quad . \quad . \quad (16c)$$

The indicated air speed and Mach number are derived from true air speed using the standard relations:

$$\rho V_T^2=\rho_0 V_i^2;\ M_n=\frac{V_T}{c}\sqrt{\left(\frac{t_0}{t}\right)} \quad . \quad (17), (18)$$

The appropriate compressibility errors must be added in since simulators must simulate defects in a system in addition to correct operation.

The position of the ball indicator is determined by resolving the vertical and side accelerations.

$$\sin\eta_b=\frac{\dot{v}}{g}=\frac{Y'/m-rV_T}{g} \quad . \quad . \quad (19)$$

The principal element of side force in a turn with no sideslip is the resolved gravitational component $g\cos\theta\sin\phi$, hence:

$$\frac{\eta_b}{V_T}=\frac{\frac{g}{V_T}\cos\theta\ \sin\phi-r}{g} \quad . \quad . \quad (20)$$

when η_b is small.

If desired, the air speed on the L.H.S. may be assumed constant at approach value since it affects only the instrument sensitivity and not the zero.

The scheme of a computer for performing the operations discussed is shown in Fig. 8.

It will be seen that the upper half of the diagram is concerned mainly with rotational and the lower half with translational effects. In the rotational section, the couples L, M and N are derived from stability data as interpreted in the computer and fed through the inertia systems where quotients L/A, M/B, N/C are produced. The p, q, r systems are integrators working on the above values of $\dot{p}$, $\dot{q}$, $\dot{r}$ (L/A, M/B, N/C), and their outputs therefore represent the angular rates.

Resolution now gives the forms of $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$ as in equations (15a), (15b), (15c) which on integration yield the gyro compass and attitude angles ϕ, θ, ψ.

The quantities computed to initiate the linear operations X', Y'/mV_T and Z'/mV_T, are called force effects.

X is fed through the mass system to produce X'/m which is integrated by the V_T system to give true air speed. Angle of attack and sideslip angle are found by computing $Z'/mV_T - r$ and $Y'/mV_T + q$ and integrating.

Similar procedure is used for each of the other variables represented.

Instruments are operated from the servos marked X, using magslip or teletorque transmitters or similar devices in the general case. If the instrument has a milliammeter movement it is driven from a potentiometer and where the frictional resistance is large a small follow up servo is used to drive the pointer.

An example of the solution of a specific flight problem by the computer is shown in Fig. 9 which shows the basic quantities concerned with pitch stability and their inter-relation.

Simpkin and Wood[11] [8] have also discussed these problems.

The movement of the elevator (η) produces a change in pitching moment (M) which is integrated to give rate of pitch (q). This affects pitch angle (θ) and angle of attack (α) again as a time integral. The change in pitch angle causes the aircraft to climb or dive, thereby changing air speed (V_T).

The angle of attack and air speed are related because induced drag, which is a function of angle of attack and air speed, affects air speed through $(X/m)dt$, while lift also a function of both quantities affects angle of attack through $(Z/m)dt$. The mutual interaction selects new values of α and V_T.

As a result of the changes in rate of pitch, angle of attack and downward force Z', the pitch derivatives m_q, $C_{D(\alpha)}$ and $m_{\dot{w}}$ are also changed, thereby reflecting the attitude changes back to the input of M.

Equilibrium is subject to the condition that the total changes in M, X and Z' are simultaneously reduced to zero. As with all closed loop systems involving time delays, the response is exponential or oscillatory in character, this latter effect being known as the pitch phugoid oscillation.

6. The Atmosphere

The properties of the atmosphere affect the flight and engine performance of a jet aircraft so much that it is necessary to reproduce these properties exactly in the simulator.

I.C.A.N. standards define the temperature of a mean atmosphere in terms of sea level temperature by the graphs shown and all the other properties of the atmosphere must be linked to these graphs.

The pressure is given by

$$p = p_0 \left(\frac{t}{t_0}\right)^{-5\cdot256} \exp\left\{5\cdot256\,\frac{(t-t')}{t}\right\}$$

where t_0, t and t' are ground temperature, ambient temperature below tropopause, tropopause temperature and temperature obtained by extrapolation through the tropopause.

Density is given by $\rho = p/RT$.

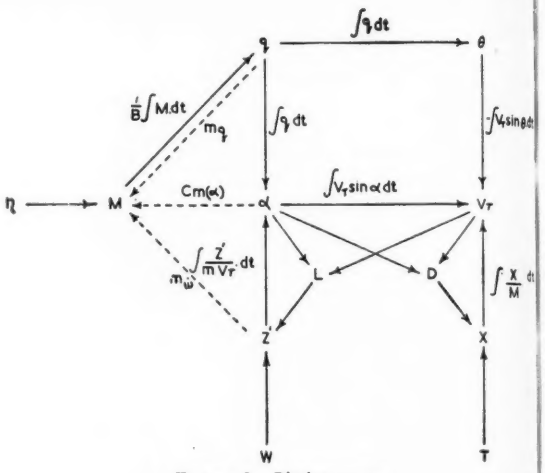

FIGURE 9. Pitch system.

The temperature as given by the computer producing the graph (Fig. 10), is modified by the addition of a term $1\cdot32\,(V_i)^2/(100)$ before feeding to the instrument to allow for compressibility rise of the ambient temperature, *i.e.* as in the aircraft the simulator O.A.T. indicator shows total temperature.

In an atmosphere system of good design the only inputs necessary are ground pressure and temperature, ground altitude and tropopause altitude. The computer evaluates all other effects.

7. Boundary Conditions—The Ground

The significance of the ground as a boundary condition of flight is at first a little difficult to realise. It has always served as the platform on which aircraft are stored, manoeuvred, accelerated and braked, given flying speed and finally lifted into flying attitude. It has performed these functions in such a passive and unobtrusive manner that except when things go wrong its characteristics are seldom noticed.

The ground has a profound effect upon the manoeuvrability of an aircraft at zero altitude whether flying or on the ground. Apart from its action in producing extra lift and nose-up pitching, it also forbids descent and nose-down attitudes and makes available additional braking, lifting and steering facilities.

The computer must therefore be arranged so that when the height of the aircraft above ground is zero the appropriate affects as indicated above are introduced.

These may be summarised as follows:

Air speed zero—complete stability in all directions.

Air speed low—braking and steering.

Air speed medium—as above, the pitching moment increasing to the point of lifting the nose wheel off the ground. Loss of N.W. steering, change of angle of attack and pitch angle in unison.

Take-off air speed—lift approaches weight, the pressure comes off the wheels, braking control is lost, particularly differential, the roll system becomes aerobatic, a small extra pitch angle causes

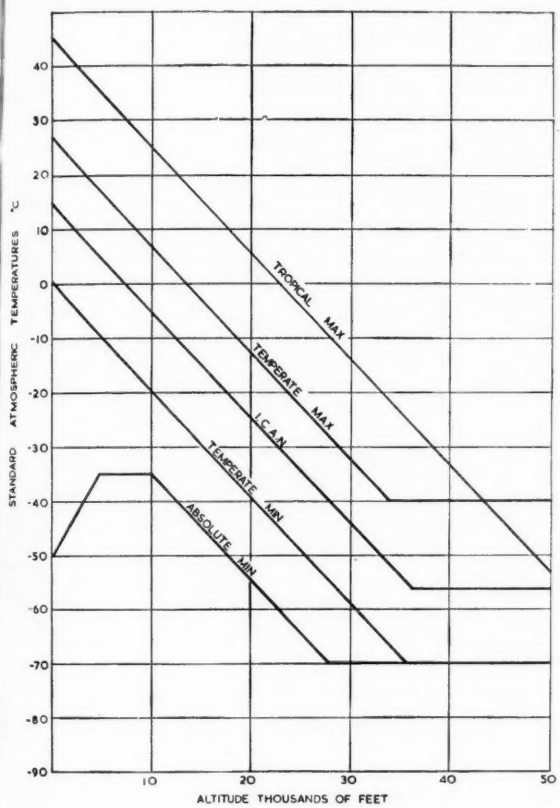

FIGURE 10. I.C.A.N. temperature law.

lift to exceed weight and vertical movement of the aircraft ensues, making the system fully aerobatic. The simulator is "off the ground."

8. Engine Computers

As described in a preceding section, the basic aerobatic and aerodynamic equations are similar for all aircraft. In the case of engines, this is not so, there being at least nine distinct types of engine in current use. 1. Pure jet. 2. Turbo-prop. 3. Ram jet. 4. Pulse jet. 5 Solid fuel rocket. 6. Liquid fuel rocket. 7. Petrol I./C. 8. Diesel I./C. 9. Compound.

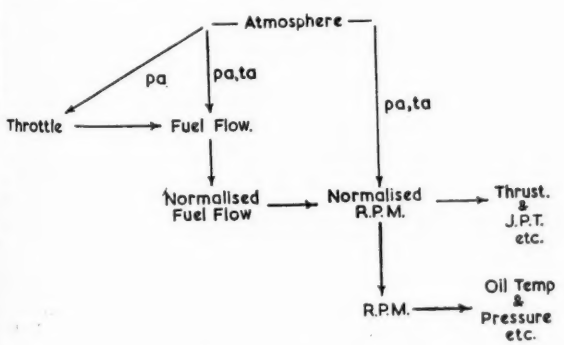

FIGURE 11. Jet engine computer.

Most simulators so far use pure jet, turbo-prop. and petrol I./C. engines, the majority being pure jets.

None of the propeller-turbine simulators has yet been delivered.

THE PURE JET

This is the simplest of power plants to simulate because it is almost entirely thermodynamic in operation. A quantity of fuel determined by the throttle and the atmospheric pressure is fed to a device which, without any further control, rotates at a stable speed with all other parameters such as jet pipe temperature, thrust and so on uniquely determined.

The number of empirical quantities is reduced to a minimum because when the fuel flow and r.p.m., or r.p.m. and j.p.t., or r.p.m. and thrust are multiplied by appropriate dimensionless functions of pressure and temperature, as indicated by thermodynamic theory, the resulting pairs of quantities, which are called normalised or non-dimensional quantities, are each related by a single family of graphs with air speed as the only independent parameter.

Engine performance figures for jets are nowadays normally given in this form by the manufacturers.

The ancillary devices in a jet engine are simple and straightforward in principle and hence present few difficulties as long as the circuit to engine analogy is maintained.

PISTON ENGINES

The jet engine has substantially constant efficiency (lb. thrust/lb. hour) over a wide range of r.p.m's. There is therefore a single matching process to be carried out associated with the size of jet orifice, except when an after-burner is fitted and fuel economy is effected by throttle control.

Internal combustion engines on the other hand have one speed at which they operate most efficiently and the power off-takes, the propellers, have to be so arranged that they load the engine variably to maintain this r.p.m. over a wide range of mixture settings and pressure and temperature changes. This means that in a multi-engined aircraft, all the r.p.m's. are similar which in turn produces severe beat effects uncomfortable to passengers

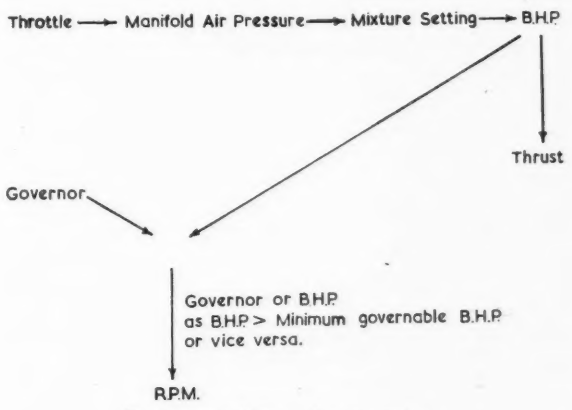

FIGURE 12. I/C engine computer.

and harmful to the structure. It is therefore necessary to associate complicated synchronising and governing mechanism with variable pitch airscrews to produce smooth and efficient synchronous running.

All these factors must be, and are, built into simulators to produce the correct operation of all controls in the system. The resulting computer is much more complicated than the pure jet computer and has many more external controls. The form of the computer is determined largely by the form taken by the r.p.m. governing and synchronising system in the aircraft.

Figure 12 gives no indication of the complexity of the control systems.

THE PROPELLER TURBINE ENGINE

This engine is by far the most difficult to simulate because it has two almost independent parts, the thermodynamic section (compressor turbine and compressor) and the propeller section (propeller turbine and propeller). The best operation is obtained when the propeller turbine is rotating at approximately the same speed as the compressor turbine.

Each part produces its own element of thrust and has its own instrumentation and control system corresponding approximately to those of the pure jet and piston engine propeller system, with the additional complication that the two systems are interdependent.

No simulator for a turbo-prop engine has yet been completed, although two are expected to be delivered early in 1954 and it will be interesting to watch their progress.

FUEL SYSTEMS

Efficient climb and cruise control, particularly for jet aircraft is the modern operator's greatest worry since every pound of fuel carried is potentially a pound of payload left behind. For this reason, the simulator for a given aircraft must compute accurately the fuel flow and fuel contents, so that cruise control may be effectively practised. To do this it is necessary to simulate completely the fuel scheduling system, including the action of boosters, high pressure fuel pumps, high and low pressure cocks, cross-feed, jettison and so on.

The fuel system is therefore quite complicated. The processes of division of fuel demand between tanks under cross feedings and isolated conditions are based normally on an analogue in which the flow of electrical current is the quantity analogous to the flow of fuel.

CABIN PRESSURISATION

The high standard of comfort of modern passenger aircraft is largely produced by correct regulation of cabin pressure, temperature and humidity conditions and considerable effort is made to control these. Although in a simulator the actual cabin conditions are not under the control of the engineer because the simulator is not pressurised, the adjustments of the system take up a fair amount of flying time in addition to their effect on drills and operational performance and hence are simulated on instruments.

A further feature which is significant in the operation of jet aircraft where the air supply is tapped from the engine compressor casing, is that the rapid descent economically desirable in aircraft can only be done in safety with the throttles well back. This tends to restrict the air supply and a mean r.p.m. has to be selected to give adequate mass flow to the cabin, hence the cabin pressurisation system tends nowadays to govern descent procedure.

The quantities for which an analogue must be found in the computer are the mass of air in the cabin and the total heat in the cabin. These are produced by integration of the mass flow and heat influx rate. As both the latter quantities represent flow they are simulated by a current analogue. Full account is taken in the computer of the effects of mass flow valves, temperature control valves, spill valves, refrigerator valves, safety valves, discharge valves, O.A.T. and blower temperature rise.

AUTO-PILOT

The standard auto-pilots used in Great Britain are Smith type S.E.P.1 and S.E.P.2 with military variations. Both these auto-pilots operate on rate plus datum control from gyros. The simulator computer contains servos, the outputs of which are the necessary rates and positions and which are used to replace the gyro platform, the remainder of the equipment being as fitted in the aircraft.

HYDRAULIC SYSTEMS

The basic operation of hydraulic systems is concerned with the flow of hydraulic fluid from pumps to hydraulic services, using reservoirs to cater for extreme loads or to reduce pump wear. The reservoir is essentially an integrator and is considered as such for the purposes of simulation. The operation of the services is governed by voltage in direct analogy of hydraulic pressure, the hydraulic pipe circuits become electrical circuits, the valves being replaced by switches and so on.

RADIO EQUIPMENT

It is not customary in British flight simulators to duplicate the radio operator's position, only those aids directly accessible to the pilot and co-pilot being installed. These are:

H.F. Communications
A.D.F. including A.N. Radio Range and Long Range D.F.
I.L.S. with Fan, Z and runway markers
D.M.E./V.O.R.
Intercommunication.

The communication and intercommunication facilities use circuits as far as possible identical with those in the aircraft, although the amplifiers associated are of normal commercial style to reduce cost.

All the other aids are directional in some aspects of their operational performance.

In the simulation of these therefore it is necessary to obtain data relating to the position on the aircraft, and the position of the transmitter associated with the radio aid, and by resolution to determine the relative bearing and relative range. An example of this is the A.D.F. system shown in Fig. 13.

This principle applies to D.F. and D.M.E./V.O.R. The simulation of A.N. range facilities is particularly interesting because of the somewhat complex pattern which it is necessary to produce.

It will be recalled that the A.N. range has four directions in which continuous signals leave the transmitter, the directions dividing the remaining pattern into four quadrants, in two of which Morse A's are transmitted, and in the others Morse N's. The equi-signal legs are not necessarily at 90° to each other. This aerial field pattern is reproduced by potentiometers or photoelectric devices.

The I.L.S. system relies on the relative strength of two transmitters on the same frequency but using different modulation frequencies to indicate the discrepancy between correct approach path and actual approach path.

In the simulator, voltages representing the deviations of the aircraft from the correct direction of approach in the horizontal and vertical planes are computed and used to operate the cross pointer instrument.

PLOTTING FACILITIES

Two forms of plotting facility are normally provided, one of which carries a large map representative of the whole area in which the aircraft is exercised and the other which may be located anywhere within this region to plot local exercises, such as I.L.S. approach or "circuits and bumps."

The rectangular charts used on the large area tables may be Mercator or Lambert conformal (secant conic) projections, but on the smaller tables it is usually assumed that the earth is flat.

Appropriate computers are associated with the large area tables to provide the necessary scale and direction correspondence between the flown track and the plotted track.

The small area charts may be based upon rectangular or polar co-ordinate plotting, to a large extent dependent upon whether or not an A.N. range is provided. The rectangular plotting table is normally fixed and the polar plotter chart normally rotates. This rotation is undesirable and the polar plotter is therefore obsolescent.

COMPOUND INSTRUMENTS

In efforts to simplify the pilot's task of co-ordinating the indications of several instruments, a number of composite instruments has recently been developed. An example of such a device is the Sperry zero reader. These instruments accept data from barometric capsules, gyros and radio facilities and work out the best manoeuvre for the pilot in an associated computer. In the simulation of these systems the simulator produces the necessary input data and the instrument computer is used to interpret it.

ELECTRICAL SYSTEMS

These are reproduced almost exactly as in the aircraft with generators being represented by potentiometers actuated by r.p.m. and similar devices. All currents are representative but scaled down and the current indicating meters are made more sensitive. Fuses and circuit breakers have all their normal functions and loss of services in the aircraft due to electrical failure is simulated using relays. Special circuits are provided for "popping" the fuses and circuit breakers remotely.

ENGINE AND AERODYNAMIC NOISE

Engine noise may be produced either from recordings made in the actual aircraft or synthetically, using all-electronic circuits. It is surprising to find that in some cases the synthetic noise is more true than the recorded noise. This may possibly be due to the fact that microphones, recorders and playback devices all tend to modify the timbre of the noise. Landing noise is generated synthetically.

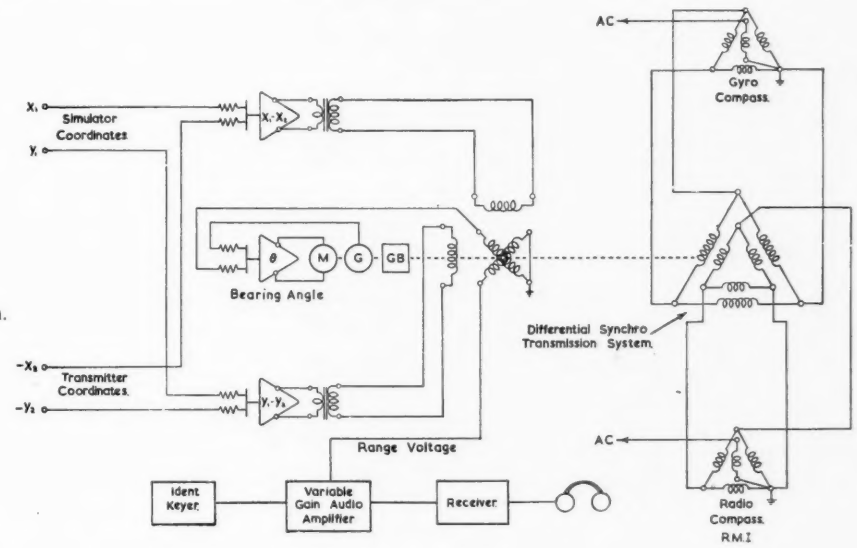

FIGURE. 13. Simple A.D.F. system.

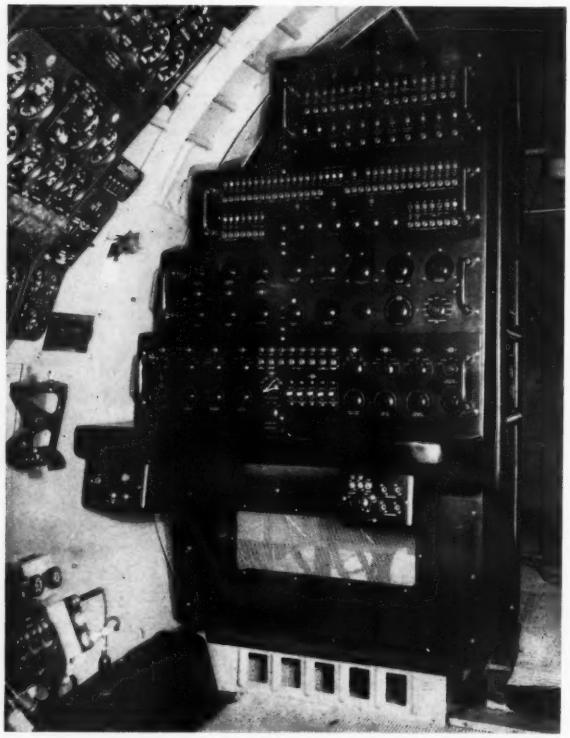

FIGURE 14. Instructor's console.

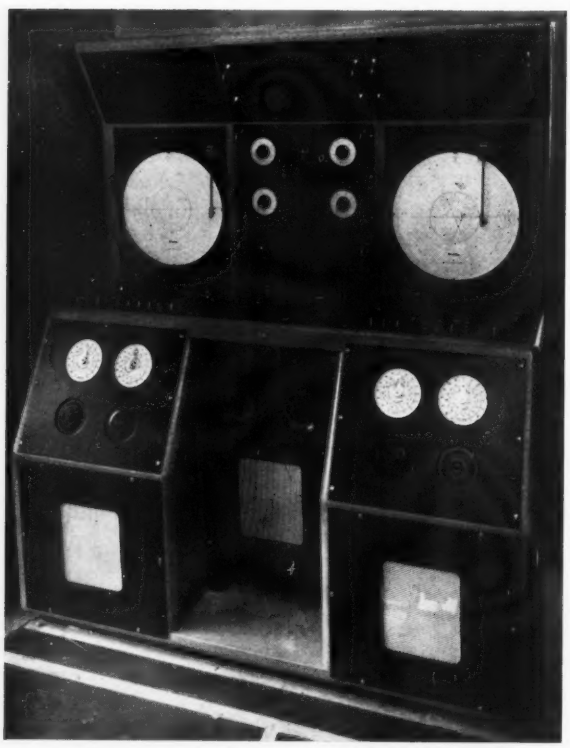

FIGURE 15. Radio aids unit.

9. The Flight Simulator of Today

The present-day flight simulator is an aggregation of all the systems already described, with more for which space permits no discussion, united with a fuselage or flight deck correct down to the last nut and bolt to produce a completeness of simulation almost impossible to visualise. The computers contain roughly 500 valves and 80 to 100 servo mechanisms consuming a total of 12 to 15 kilowatts of power from the normal 3 phase mains. The distribution systems and other wiring use up over 40 miles of wire.

INSTRUMENTS

The instruments and faults which are made to operate realistically in association with the various services in a typical civil flight simulator (Comet I) are:

Flight

Air speed indicator, machmeter, altimeter, rate of climb indicator, gyro horizon, gyro compass, magnetic compass, turn and slip indicator, accelerometer, zero reader and O.A.T. meter.

Engines

Tachometer, oil pressure indicator and oil, jet pipe and rear bearing temperature meters.

Fuel systems

Fuel flowmeters and fuel contents gauges.

Electrical systems

Ammeters for each generator, voltmeter.

Hydraulics

Blue, green and red accumulator pressure and green and red, left and right foot brake hydraulic pressure gauges.

Cabin pressurisation

Cabin altitude, differential pressure, temperature and rate of climb indicators. Mass flow and air entry temperature gauges.

De-icing

Port, starboard and tail de-icing duct temperature and fuel temperature gauges.

Radio

I.L.S. cross pointer instrument.

Navigator

Gyro compass master indicator and A.D.F. master indicator.

In all, 98 instruments of 31 different types are operated by a total of over 200 input controls and switches. Over 70 on/off indicators and lights are also operated by the system.

The operation of these indicators, lights and instruments is determined by associated circuitry in which are included nearly 200 circuit breakers and fuses occurring on the aircraft electrical panel. These figures are indicative also of the extreme complication of a modern aeroplane to which the simulator must necessarily approach.

10. Instructor's Equipment

The instructor's console

This console controls a large number of failures and effects including:

(*a*) Fires in 20 zones of the aircraft.
(*b*) Failure of 8 supplies by remote operation of circuit breakers.
(*c*) 9 flight instrument failures.
(*d*) 7 hydraulic failures.
(*e*) 6 undercarriage faults.
(*f*) Errors to all engine and fuel system instruments (30).

In addition to these, the other systems are influenced by additional faults, giving a total of about 120 distinct fault conditions.

Fifteen basic data inputs to the computor including gross weight, ground pressures, C.G. and so on are also provided at this position.

Figure 14 shows the layout of this equipment.

The radio aids unit and recorders

The radio aids unit (Fig. 15) is arranged to give full operation including failures and deficiencies of all radio facilities in civilian use in Europe, each aid being independently adjustable for different transmitter locations. The large area recorder, Fig. 16, is electrically linked with the radio aids unit, co-operating with it to switch in automatically the small charts at appropriate points and to produce long range D.F. facilities.

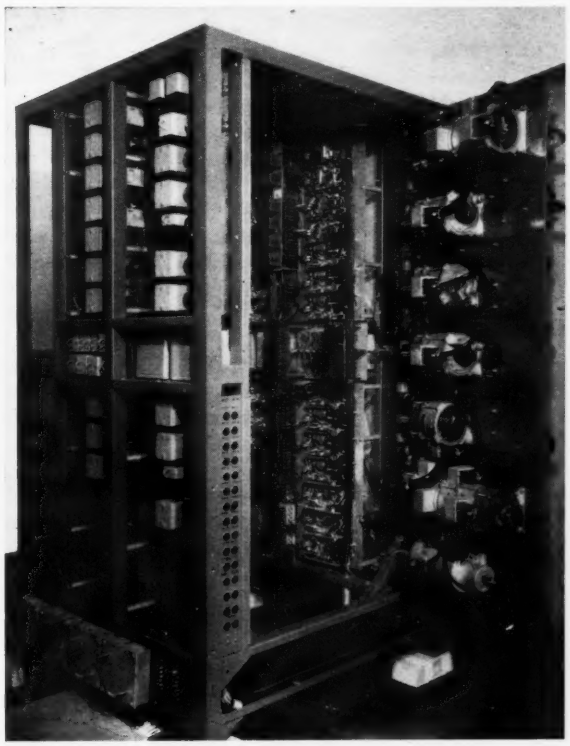

FIGURE 17. Computer cabinet.

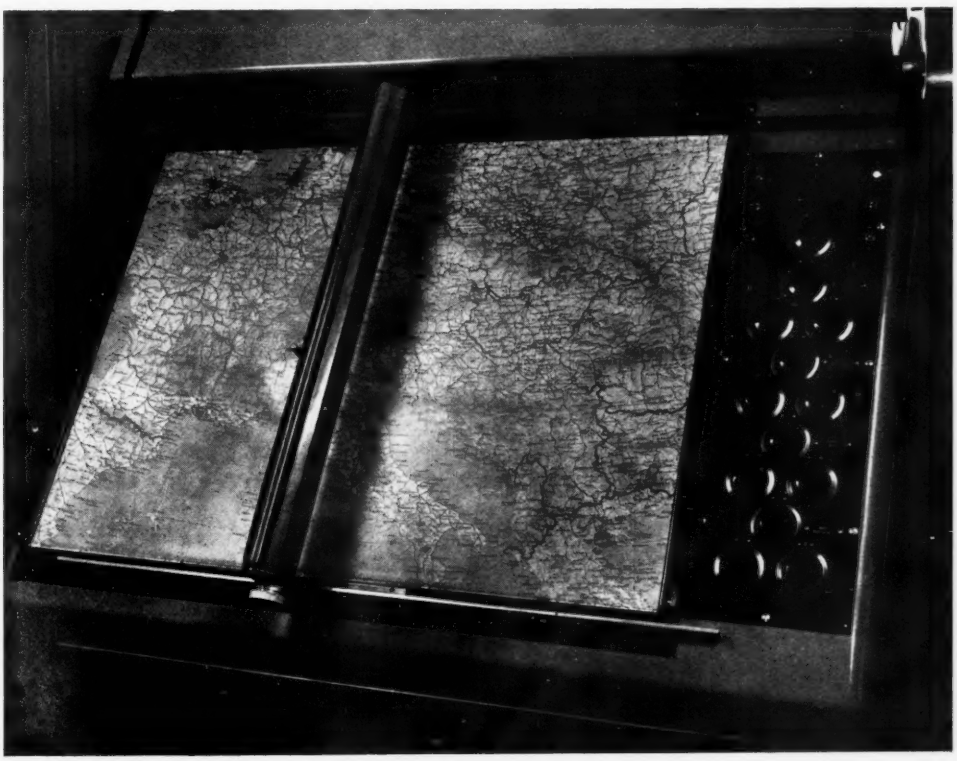

FIGURE 16. Long range recorder.

11. Conclusions

Enormous strides have been made in the field of flight simulators since their inception only five years ago. In addition to the obvious refinements of technique, their scope is also rapidly increasing. As an example of this, the Comet I flight simulator of British design embodied simulation of hydraulics, fuel systems, auto-pilot, cabin pressurisation, de-icing, tuning in facilities for station selection, zero reader, a large area plotting table and long range D.F. facilities, not included in previous simulators. New flight simulators will have altimeter systems capable of ± 10 ft. accuracy from zero to 50,000 ft., rapidly interchangeable ident selectors for radio aids, improved I.L.S. systems, improved gyro compass systems, exact atmosphere simulation and many other interesting and novel devices.

In the military flight simulators at present under development, provision is made for attachment of many of the standard radio and radar trainers currently in use with the Services, such as Gee and search radar. These will enable the crew to carry out full-scale exercises against imaginary enemy craft. Of great value in peace, these devices will be of inestimable value in a future war.

Simulators are now being ordered in increasing numbers and practise with those already in use has shown beyond all doubt that they enable training to be carried out far more thoroughly and in complete safety, while at the same time being much cheaper and using fewer aircraft.

The art is advancing so rapidly that each day brings new ideas. Despite this, a general technique is being developed to standardise those sections of the computers which are capable of such treatment in order to reduce the costs and bring about more speedy deliveries.

So far, most things for which a requirement exists have been simulated, but this is not so in all cases. Paramount among the features for which a satisfactory solution has not yet been found are visual approach, astro navigation, search radar and realistic "g" forces. The latter of these will probably never be satisfactorily solved as it is contrary to the fixed base principle on which all modern flight simulators are designed. With the others, the cost of development is the greatest deterrent.

In the military field the rapid development of new types of aircraft and missiles is creating many problems of training and operation in the solution of which the flight simulator and kindred devices will play a very important part.

ACKNOWLEDGMENT

The authors are indebted to the directors of Redifon Limited for permission to publish this paper and would like to express their thanks to all members of the organisation who, directly or indirectly, have made contributions to it.

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Discussion

E. LLOYD THOMAS: As one who regarded aeroplanes as nasty unreliable things he was naturally attracted by the idea of a simulator since it seemed to offer all the advantages of flying, with none of the disadvantages.

For the larger and slower types of aircraft it might be acceptable to neglect the effect of acceleration on the crew, but it seemed to him that the absence of acceleration forces must detract considerably from the realism when simulating small high speed aircraft, where the accelerations were likely to be fairly high.

One remark which struck him on glancing through the advance copy of the paper was the statement that "A simulator is good for at least 75,000 hours." Assuming that the equipment might be used for 300 days a year and for 10 hours a day, this meant a life of something like 25 years! Personally he would hate to try to design one of those simulators and hope that it would still be working at the end of such a time. Perhaps the authors meant to imply that the equipment would survive for 25 years with regular servicing and component replacement.

Again, what order of development time was involved in designing this apparatus, the number of man-years, if they liked? He appreciated that each new simulator

drew on the design of the previous one, but there must always be a number of fresh problems to be solved for each application.

On the subject of the choice of system for the various stages of computation, he believed he noticed somewhere a statement to the effect that for really accurate computation it was essential to employ an A.C. carrier system. He strongly disagreed with that remark. If one required the ultimate in accuracy from a computing device it was quite feasible to use an entirely D.C. system; but it did involve considerable complication. However, if he were presented with the same problem as the authors he would probably do as they had done and employ electro-mechanical computation.

As to the accuracy of the integrators; although there was no specific indication in the paper, it was mentioned in the film that after two hours or so flight one might expect the aircraft position to be accurate to within about 2 per cent. This was quite an achievement; in terms of electronic integrators it implied a very large time constant indeed, and very low drift.

The electro-mechanical integrator employed in the simulator was described by Dr. Cutler as a velodyne, although the amplifier and tacho-generator appeared to be A.C., not D.C., devices. If the amplifier really did function on A.C. then he would be interested to have more details of the generator, which produced, presumably, an alternating E.M.F. of carrier frequency, but varying amplitude according to the speed of the shaft.

The last part of the sub-section of the paper headed "Integration," dismissed electronic integrators in one paragraph! This included the statement:—

> "The leakage across ordinary condensers through the dielectric causes drift which at large values of the integral of the input variable can be very serious and for long term accuracy and stability drift compensators or special polythene dielectric condensers must be used."

There seemed to be some confusion here between "drift" and the effect of capacitor dielectric leakage. His definition of drift was "a spurious signal in an amplifier which, when the amplifier is used as an integrator, causes the output (in the absence of an input signal) to drift *away* from zero."

The effect of capacitor leakage, however, was to make the output of the integrator *return* gradually to zero after it had been given some finite value.

Finally, still on the subject of integrators, should not the dielectric of the integrator capacitor be polystyrene, not polythene, as stated?

J. C. KING (Hon. Secretary, Preston Branch, *Assoc. Fellow*): As Honorary Secretary of one of the Society's Northern Branches he felt the importance of Main Society lectures away from London, and was pleased to know that in Belfast they had turned up very well indeed to support this, the second Main Society lecture to be held there.

He would like to propose a very sincere vote of thanks to the lecturers as they had dealt skilfully with a very difficult subject. He could not say that he understood it all, but having heard this lecture he now knew a lot more about flight simulators and what they could do. The application of these training aids to civil aviation was important if safety in flying were to keep abreast of technical improvements and if the public were to turn more and more to civil aircraft as a reliable means of transport.

The Authors' Reply

The authors were pleased to receive Mr. Lloyd Thomas' questions and regretted that because of shortage of time they were unable to answer them at the meeting. The first of the points which he raised was a very vexing one and one on which very much discussion had taken place.

In modern aircraft, longitudinal and sideslip accelerations were small compared with the vertical accelerations experienced in tight turns and when pulling out from dives. These vertical accelerations were the most important to produce.

Genuine accelerations could only be obtained by permitting the simulator itself to perform the appropriate aerobatics, which was clearly impossible.

It was believed that one trainer manufacturer had attempted to solve the problem by strapping the pilot into his seat and inflating an air cushion, on which he sat, at appropriate times. Whether the reaction on the pilot's shoulder straps detracted from the simulation was not known.

In a simulator recently completed, the movement of a bungee weight attached to the elevators was counterfeited and it was reported that the pull felt on the stick from this weight, plus the movement of the accelerometer, went far to produce the sensations of moderate g.

The life of a simulator was given as 75,000 hours but this did not mean, as Mr. Lloyd Thomas assumed, that this represented 25 years at 10 hours per day. An operator with a simulator would normally use it to the maximum, which probably meant up to 15 hours actual use with intervals up to 2 or 3 hours for briefing time. As this left only a few hours for maintenance, both remedial and preventative, the probability was that the simulator would run continuously all the week with the week-end devoted to modifications and adjustments. At this rate the figure quoted meant ten years. This ulitisation could only be obtained by prompt and efficient repair and replacement service.

It was very difficult to estimate with any great accuracy the development effort put into a simulator prototype. The fundamental circuit design was completed in less than a year by about half a dozen highly skilled engineers. From that stage the job was taken up by a very large body of supporting staff whose

responsibility it was to design electronic components, servos, instruments, structures and all the other highly complicated sections which made up a simulator. The time from start to finish was of the order eighteen months to two years.

They felt that Mr. Lloyd Thomas supplied his own answer to the question on the choice of carrier. Feasibility was not a suitable criterion of choice; the problem was so complicated and the time available for design so short that the method adopted must be intrinsically capable of the required high accuracy with the minimum of adjustment. Only the A.C. method had the desired robustness.

The query concerning the "velodyne" integrator was purely a matter of definition, as was also that concerning " drift." There was no reason to suppose that the name " velodyne " inferred any preference for A.C. or D.C. although it must be admitted that the early " velodynes " were D.C. operated; there was at that time no option, the cheap and accurate drag-cup type A.C. generators as widely used in modern servo systems did not seem then to be available. Their definition of " drift " in an integrator was undesired variation of the integral from any cause.

As Mr. Lloyd Thomas pointed out, the dielectric in the plastic film low loss condensers should have been polystyrene and not polythene. The error had been removed from the text.

Meteorological Services for the Comet*

by

E. CHAMBERS

(*Meteorology Superintendent, British Overseas Airways Corporation*)

THE SUPPLY OF METEOROLOGICAL INFORMATION for Comet operations began long before the first prototype was in the air, since information on aerodrome temperature and pressure and ambient air temperature up to 40,000 ft. was required to assess engine performance. Thus it was found that extremes of temperature at 40,000 ft. range from about −80°C. over the United Kingdom to −35°C. over Northwest India and performance curves were constructed to cover this range.

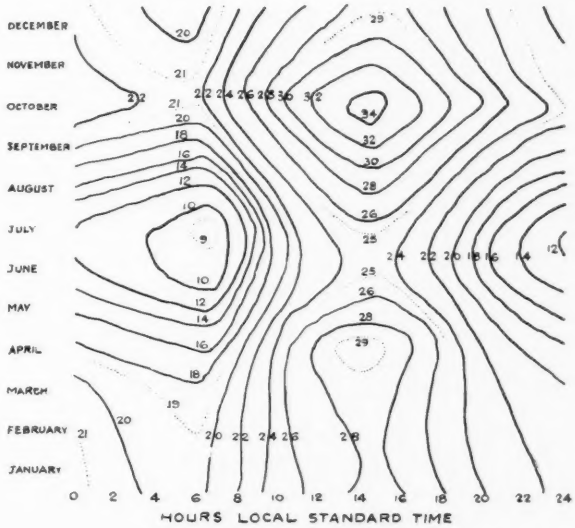
Statistics on low temperatures were required in connection with the performance of the de-icing system on descent; statistics on high temperatures were required for engine performance throughout flight.

Since then, there has been an increasing requirement for more detailed statistics of meteorological elements over various air routes in order to prepare route analyses to ascertain payload possibilities. Having decided that the aircraft will be able to operate safely and reasonably economically over a given route, still further detail is required to arrive at the best schedule to meet both the operational and commercial requirements. It is often difficult to integrate all requirements and to arrive at a schedule which will enable satisfactory payload to be carried with regularity. It is important, moreover, that the schedules should be reasonably elastic; thus it would be unwise to schedule a service through a hot place at, say, 11 a.m. if from 12 to 4 p.m. the temperature were likely to prove unacceptably restrictive.

It is well known that aircraft cannot take-off at maximum all-up-weight from all aerodromes under all conditions of pressure and temperature experienced at these aerodromes. In extreme cases, a rise of 1°C. or an increase of 100 ft. in pressure altitude, or a decrease of one knot in runway wind component, will reduce the maximum permissible take-off weight by the equivalent of one passenger and his baggage.

Ideally, it is desirable to evaluate the take-off condition for a given aircraft for each aerodrome, where take-off limitations occur, for each hour of the day over a number of years and so estimate the permissible take-off weight for different times of the day on a monthly or seasonal basis. This would be a laborious process and, in many cases, the necessary meteorological data are not available. However, for certain aerodromes close approximations to this procedure have been followed. For example, temperature is often a limiting factor and it has been found necessary to obtain data on the mean value of temperature for all hours of the day throughout the year, together with the corresponding standard deviations. Provisional isopleths of temperature for Livingstone (Northern Rhodesia), prepared by the Air Ministry are shown in Fig. 1. Thus by applying the standard deviation it is possible to read off the temperature which will not be exceeded on X per cent. of occasions at any hour of the day during any month of the year.

The take-off condition is obviously improved if there is a favourable component of wind along the runway and tables showing the correlation of surface temperature with runway wind component have been compiled to assist in long-term planning. A table for Colombo is shown in Fig. 2 and shows the effect of the sea breeze in the afternoons. It follows, for example, that in May there is almost invariably a wind component of 4 knots or more when the surface temperature exceeds 30°C. It is usual to use the geographical altitude as the take-off pressure altitude. This is penalising at a high altitude tropical station. Thus at Salisbury (Southern Rhodesia) the mean pressure altitude is 300 ft. lower than the



(Subtract 2 hours for G.M.T.)

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ISOPLETHS OF MEAN TEMPERATURE °C
LIVINGSTONE 17° 50′ S 25° 49′ E 3161 FEET
STANDARD DEVIATIONS °C (INTERFOLATED)

	J	F	M	A	M	J	J	A	S	O	N	D
0200	1½	1½-2	1½-2	2	2-2½	2½	2½-3	2½-3	2½-3	2½-3	2½	2
0800	1½-2	1½-2	2	2	2-2½	2½-3	3	3	3	2½	2-2½	2
1400	4	3½	3	2½	2½	2-2½	2-2½	2½-3	3-3½	3-3½	3½	3½-4
2000	2½	2-2½	2	1½-2	1½-2	2	2	2-2½	2-2½	2½	2½	2½

FIGURE 1.

* This paper is based on a lecture given before the Brough Branch of the Society on 12th November 1952.

actual altitude of the aerodrome, while the highest of the mean monthly maxima is over 100 ft. lower than the geographical altitude.

Having decided on the main staging posts over the route, an estimate of fuel requirements over each sector must be made. Ambient air temperature and the equivalent headwind are required for this purpose and suitable alternates to the departure and terminal aerodromes must be nominated. If the fuel requirements are such that the take-off weight becomes excessive for any particular aerodrome, careful analysis must be made to reduce the payload penalty as much as possible. Thus selective scheduling may be necessary to achieve optimum take-off conditions at marginal aerodromes, a nearer alternate chosen, or a fuel stop introduced. Long term planning requires a vast amount of weather data, for example high level flights over new routes around the world are now being considered and winds and temperatures are required at places and heights where very few observations have been made, so that the information is becoming more and more difficult to supply.

Returning to present-day operations, some two hours or so before E.T.D. (Estimated Time of Departure) a flight plan is prepared, based on meteorological forecasts of surface wind, pressure and temperature for take-off, upper winds and temperatures and terminal and alternate weather. It is usually possible to forecast this surface pressure and temperature with a high degree of accuracy and if the take-off condition is adequate, the only thing likely to delay a Comet flight is a forecast of below limits weather at the terminal. Route weather, with the possible exception of abnormally strong headwinds (jet stream), is unlikely to delay a Comet flight. However, since the fuel carried is based on the forecast of upper winds and temperatures, the reserve in hand at any time of the flight depends on the accuracy of the forecast up to that point and, therefore, upper winds will continue to play an important part in operations.

What winds are expected and what accuracy is obtained in practice? The Meteorological Office, Air Ministry, has produced seasonal upper wind charts over the world at various constant pressure levels up to 130 mbs. (about 50,000 ft.) and corresponding charts of standard deviation. It is assumed that upper winds at any given level follow approximately a normal (circular) distribution in any given season and the charts, therefore, enable seasonal mean equivalent headwinds and

Month and Time	*Surf. Temp.* (°C)	*Component of Wind (Knots) along the Runway*									
		0-3		4-9		10-15		16-21		*Var.*	*Calm*
		22	04	22	04	22	04	22	04		
Jan.	30-34	0	0	0	1	0	0	0	0		0
0800	25-29	1	4	0	13	0	3	0	0		2
LST	20-24	2	25	0	88	0	8	0	0		8
Jan.	30-34	8	6	12	20	0	8	0	0		0
1500	25-29	23	22	19	27	0	4	0	0		2
LST	20-24	0	0	0	2	0	0	0	0		0
Feb.	25-29	3	16	1	10	1	2	0	0		3
0800	20-24	6	35	1	42	0	0	0	0		20
LST	15-19	0	0	0	1	0	0	0	0		0
Feb.	30-34	6	9	24	8	1	3	0	0		0
1500	25-29	18	28	26	9	2	1	0	0		0
LST	20-24	0	0	0	1	0	0	0	0		0
Mar.	25-29	13	61	1	30	0	0	0	0		23
0800	20-24	1	12	0	10	0	0	0	0		4
LST											
Mar.	30-34	22	9	85	2	6	0	0	0		0
1500	25-29	8	9	12	2	0	0	0	0		0
LST											
Apr.	25-29	39	48	24	5	1	0	0	0		20
0800	20-24	5	6	0	0	1	0	0	0		1
LST											
Apr.	30-34	14	3	84	0	4	0	0	0	1	0
1500	25-29	6	6	20	1	6	0	0	0		1
LST	20-24	1	1	0	1	0	0	0	0		1
May	30-34	0	0	4	0	0	0	0	0		0
0800	25-29	29	18	79	3	3	0	0	0		12
LST	20-24	3	1	1	1	0	0	0	0		1
May	30-34	3	0	75	0	15	0	1	0	1	0
1500	25-29	11	0	36	0	8	0	0	0		2
LST	20-24	1	0	1	0	1	0	0	0		0

FIGURE 2. Number of occasions (1947/1951 inclusive) of specified runway wind components associated with specified surface temperatures. Ratmalana (Colombo). Main runway 04/22.

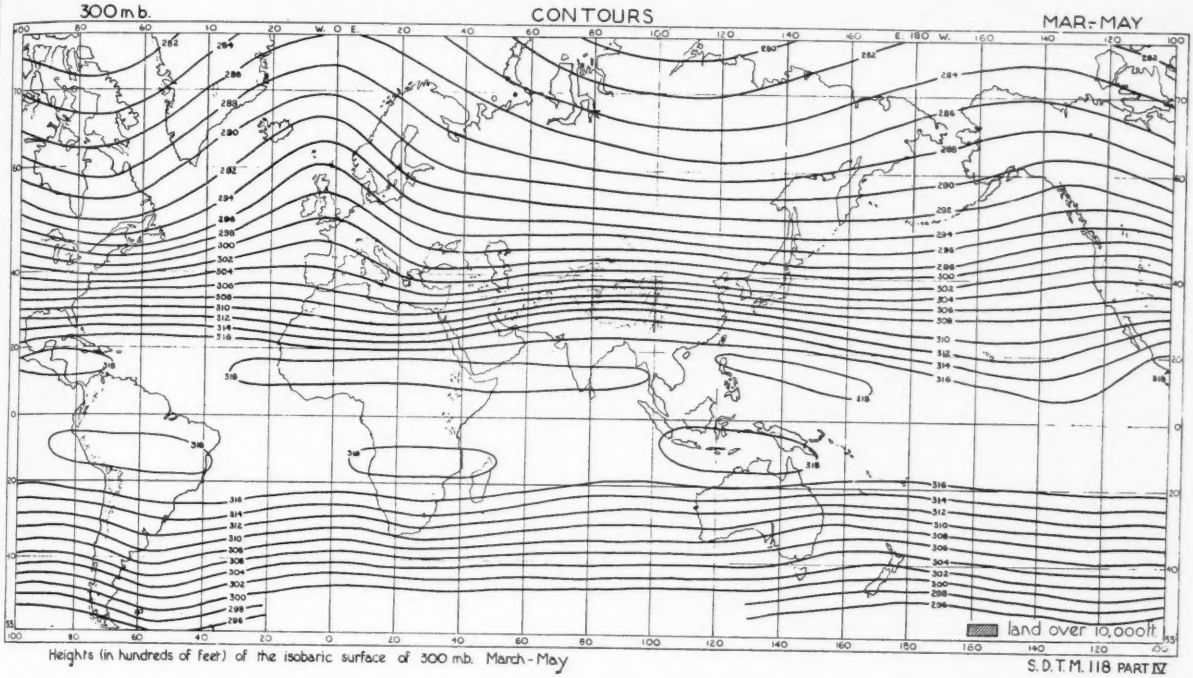

FIGURE 3.

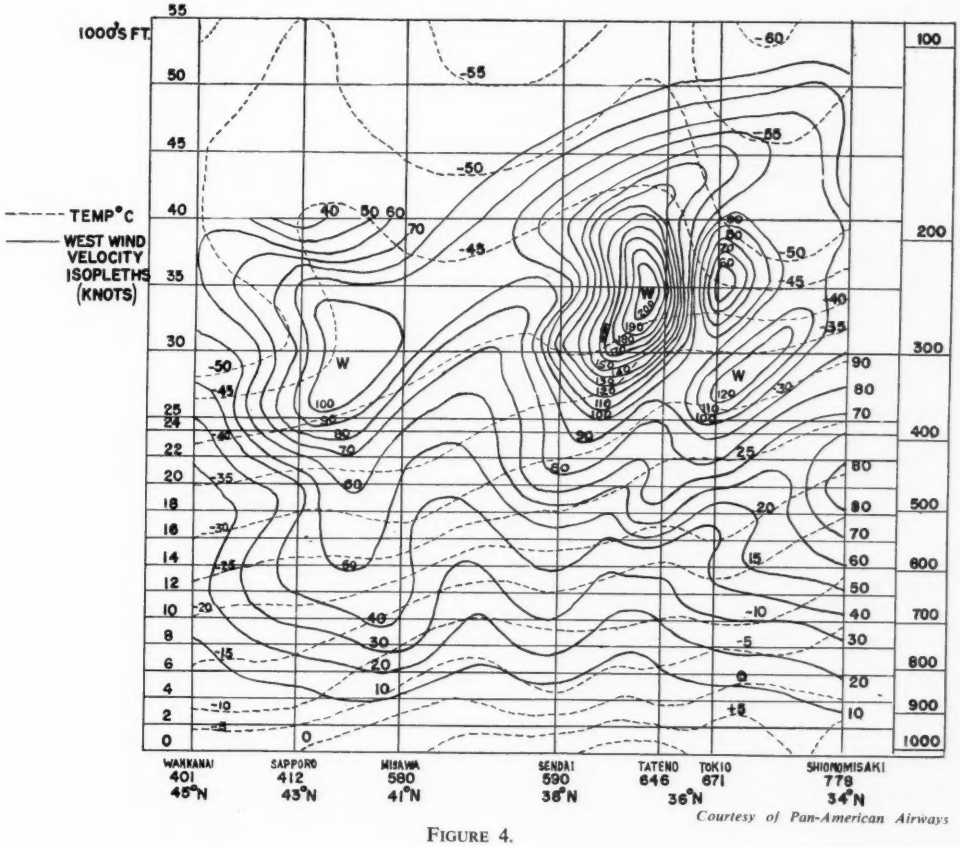

FIGURE 4.

their standard deviations to be evaluated for any given air route. This information is of particular importance for advanced planning. Over many parts of the world, however, the basic data used in the construction of the charts were very sparse and, as additional upper air observations continue to be received, the charts are periodically reviewed and amended as necessary. The 300 mb. chart for March-May is shown in Fig. 3. This chart illustrates the general pattern but is shortly to be issued in a slightly revised form.

On any particular day, especially in winter, the wind pattern might be very different from the seasonal mean or even from the monthly mean. At present, winds are measured by meteorological services by following hydrogen-filled balloons either visually by theodolite or by radio/radar methods. The former method is of very limited value and is confined to cases of relatively clear skies. The latter requires expensive equipment and specially trained personnel. In consequence, the network of high altitude upper wind reporting stations is very sparse, with the possible exception of the North Atlantic, European and (thanks probably to the Korean War), Japanese regions.

In temperate latitudes winds are usually deduced from constant pressure contour charts assuming geostrophic flow and these charts are constructed from observations of altitude, pressure and temperature measured by radio sonde. The network of radio sonde

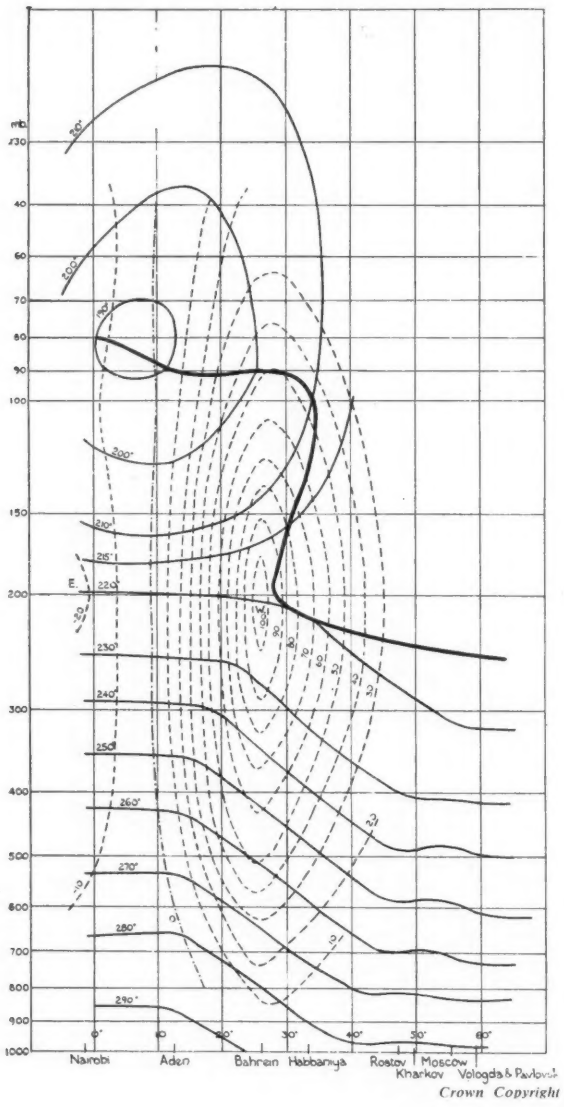

FIGURE 5. January. Atmospheric cross section at 40°E. Longitude showing mean temperature and mean East-West wind component. (Isotherms are shown by continuous lines, isokinetics by broken lines, the zero isokinetic by a chain-dotted line and the tropopause is shown by a heavy continuous line.)

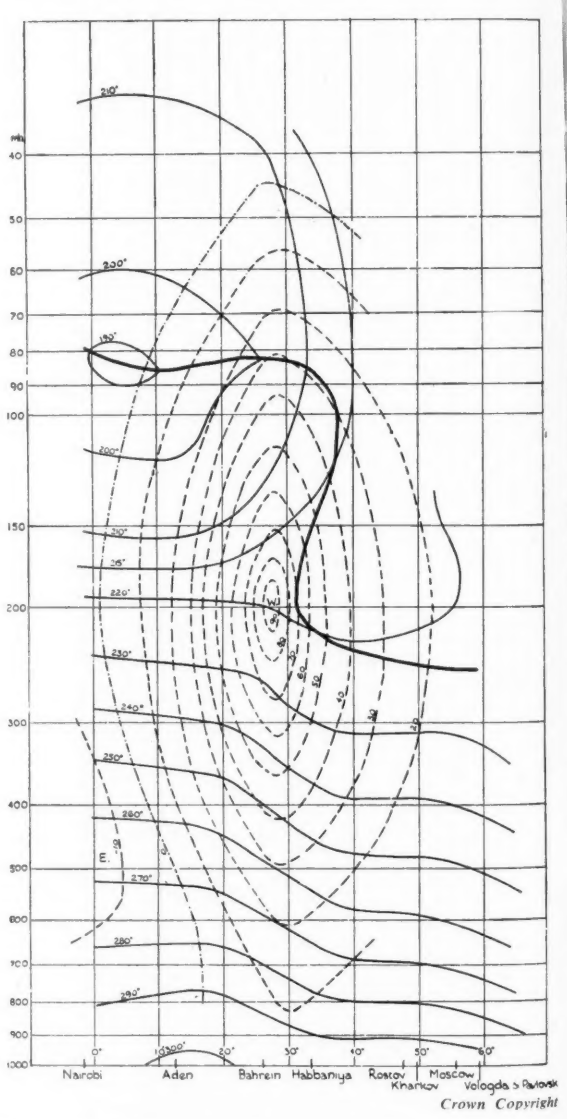

FIGURE 6. April. Atmospheric cross section at 40°E. Longitude showing mean temperature and mean East-West wind component. (Isotherms are shown by continuous lines, isokinetics by broken lines, the zero isokinetic by a chain-dotted line and the tropopause is shown by a heavy continuous line.)

stations is slightly better than that of radio/radar winds. Errors in radio sonde observations, however, increase with height and with various different types of equipment in use over an area the different errors are often irreconcilable. Thus at Comet altitudes, the charts are often difficult to construct so that the forecaster may sometimes be without a true actual distribution on which to base his forecast. Even assuming that the observations permit an actual chart to be constructed, it is usually 6 hours or more after the time of observations before the data can be collected and analysed. Furthermore, winds in temperate latitudes, *e.g.* North Atlantic, undergo quick changes and closed "lows," with somewhat erratic movement, often exist. Thus over the sector London/Rome, winds may be southwest 100 knots on one chart, and northwest 100 knots on the next, and the changes are difficult to forecast.

Ageostrophic terms loom large when development is taking place and unless the upper air situation is fairly settled, the standard of forecasting is low. Gradients slacken and tighten within very wide limits at times and there is insufficient knowledge to forecast these changes with the data available at the present time. Even over Europe and the North Atlantic territories, full radio sonde observations are made not more than twice daily and over most other areas not more than once daily.

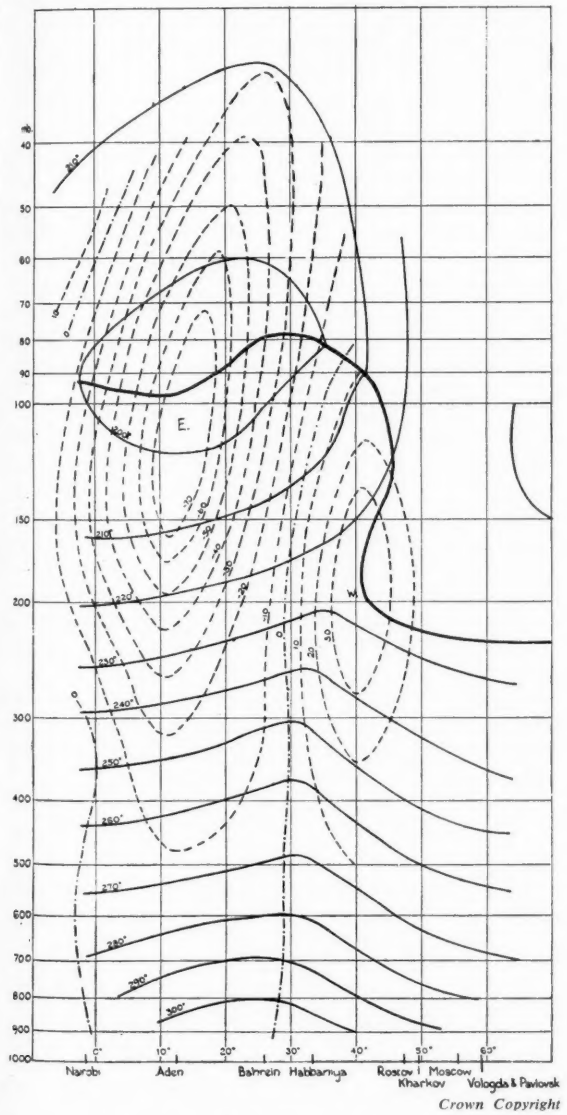

FIGURE 7. July. Atmospheric Cross section at 40°E. Longitude showing mean temperature and mean East-West wind component. (Isotherms are shown by continuous lines, isokinetics by broken lines, the zero isokinetic by a chain-dotted line and the tropopause is shown by a heavy continuous line.)

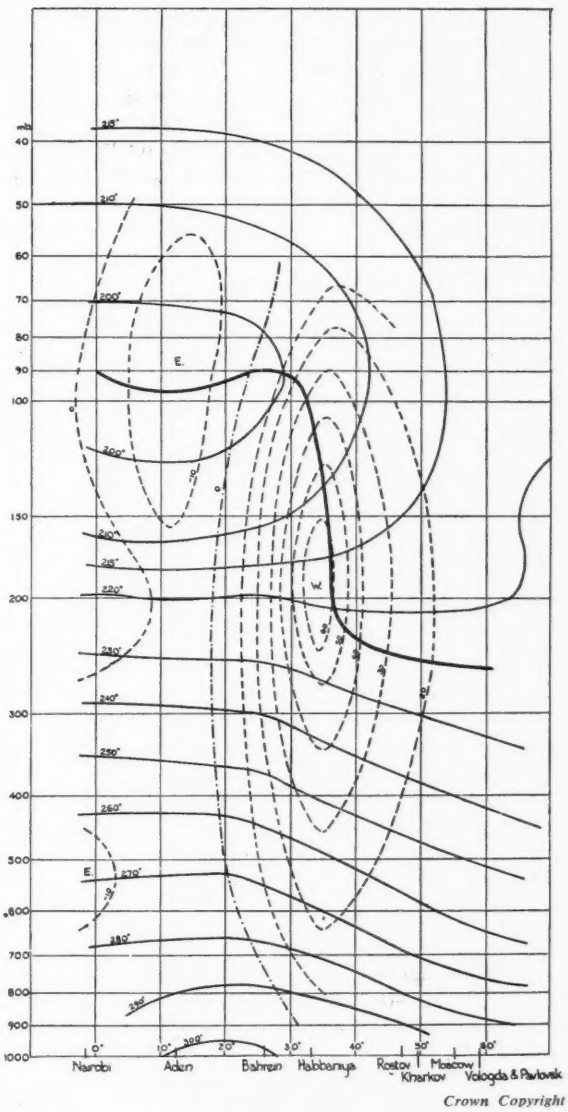

FIGURE 8. October. Atmospheric cross section at 40°E. Longitude showing mean temperature and mean East-West wind component. (Isotherms are shown by continuous lines, isokinetics by broken lines, the zero isokinetic by a chain-dotted line and the tropopause is shown by a heavy continuous line.)

Thus the forecaster is working with upper charts from 6 to 18 hours old, while the 3 to 6 hourly surface charts offer much less guidance at 200 mbs. than they do at the lower levels. In fact, present contour techniques appear to be inadequate for forecasting at the 200 mb. level, and there is an urgent need for the more rapid dissemination and charting of basic upper air data. An example of the complexity of the upper wind pattern in winter is given in Fig. 4 from upper wind observations over Japan. Jet streams of this magnitude obviously are of great operational significance.

The geostrophic wind at any altitude is the vector sum of the geostrophic wind as measured from a surface chart and a thermal wind as measured from a chart of mean integrated isotherms from the surface to the appropriate altitude. Thus at high levels the winds are predominantly thermal and it is appropriate, therefore, to discuss the distribution of temperature and its association with the upper winds. In this connection, the tropopause which divides the troposphere from the stratosphere plays an important role. At the tropopause, the temperature resulting from convection in the lower atmosphere is equal to the radiation equilibrium temperature and it is to be expected that the greater convection in the tropics results in a higher tropopause there. In fact, the region of highest tropopause moves with the sun and coincides approximately with the thermal equator (latitude 0° at the equinoxes, 30°N. in July, 30°S. in January). The I.T.C.Z. (Inter-Tropical Convergence Zone) or I.T.F. (Inter-Tropical Front) lags behind and reaches approximately 20°N. in August and about 15°S. in February. Broadly speaking, the tropopause height may be conveniently classified as tropical or temperate, the former averaging about 55,000 ft., and the latter 35,000 ft. It has been shown that, at any given time, the change from one to the other usually takes place over a very short range of latitude, thus creating a marked discontinuity in the height of the tropopause over a north-south cross section of the atmosphere. Figs. 5, 6, 7 and 8 show the cross sections through 40°E., as given by Frost in a paper of the Meteorological Research Committee.

Dobson and Brewer* show that the presence of ozone in the upper atmosphere has an important bearing on the temperature of the stratosphere owing to its strong absorption in a band of infra red wave lengths which are transparent to water vapour. They explained that the distribution of ozone would account for the following observed facts:—

(*a*) the rise of temperature in the stratosphere in the tropics,

(*b*) the higher tropause temperatures over the Poles (about 40°C. higher than at the equator, except in winter when the ozone concentration decreases),

(*c*) the annual variation of temperature in the stratosphere being out of phase with that of surface and tropopause temperatures.

Meteorology and High Altitude Aviation by C. M. B. Dobson and A. W. Brewer.

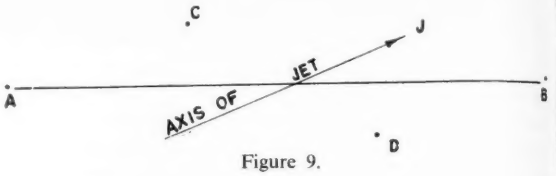

Figure 9.

The tropopause, however, often is not uniquely or clearly defined and in examining individual upper air soundings there may be evidence of multiple tropopauses or, on the other hand, the decrease in lapse rate may be so small as to be indiscernible. In temperate latitudes, the height and temperature of the tropopause are subject to seasonal and, very often, considerable day-to-day changes and although certain general properties are known which partially explain these changes, tropopause behaviour is still imperfectly understood. Consequently, changes in tropopause height and stratospheric temperature are very difficult to forecast and these problems, of course, bear some relationship to the problem of forecasting high altitude winds.

The relationship between the slope of the tropopause and the upper winds is shown clearly in Figs. 5, 6, 7 and 8. For the sake of argument these cross sections, with minor adjustments, may be considered typical of any meridian through a land mass and it will be seen that the strongest upper winds over the world are found at approximately the height of the temperate tropopause (Comet cruising altitude), and where the integrated thermal effect upwards from the surface is a maximum. Thus on the 40°E. meridian, the westerlies are at a maximum and reach over 100 knots at 26°N. in January. They move slowly to 29°N. in April and weaken to 90 knots, then move more rapidly to 40°N. by July, decreasing to 35 knots. By October, they have moved south to 33°N. and increased to 65 knots. Similar jet streams are found in the southern hemisphere and in July westerlies exceeding 100 knots occur regularly over South America, South Africa and Australia between 25° and 30°S. Because of the large temperature difference in the troposphere between the North Pacific and the vast continent of Asia in winter, the jet stream is particularly intense over Southern Japan and the strongest winds in the world are found there at tropopause levels, which coincide approximately with the cruising altitude of the Comet. The average intensity of the Jet stream is between 150/200 knots almost invariably from a direction between 250/280 degrees true and wind speeds of nearly 400 knots were observed by radar at approximately 35,000 ft. on two occasions in February 1953.

Provision has been made to carry appropriate fuel reserves, but for economy in operation it is obviously important that the day-to-day changes should be forecast with reasonable accuracy. It is uneconomical to carry excess fuel reserves, even though this may not detract from payload, since extra fuel is consumed in order to carry the extra weight. To increase the all-up-weight of the Comet from 103,000 lb. to 105,000 lb., over a 1,500 mile sector, assuming a mean temperature of standard plus 15°C. and a 50 knot headwind, would

result in 1,200 lb. extra fuel being consumed, *i.e.* there is only 40 per cent. of the extra fuel available as reserve. In addition, the maximum permissible landing weight must not be exceeded and, short of making provision to jettison fuel, the captain of the aircraft must give detailed thought to the situation before arranging to uplift extra fuel for "the wife and children."

Upper wind forecasting for jet aircraft is of particular importance over sectors where very strong winds occur, especially when the speed may change considerably with respect to time and/or space (jet streams). Over tropical sectors, say between 20°N. and 20°S., the winds appear to be fairly constant and it is rare for speeds to exceed 50 knots at 40,000 ft. Thus apart from possibly long range west to east flights, the seasonal or, in some cases, the monthly mean wind would appear to be adequate for jet operations. Unfortunately, there is not yet sufficient data available over most of the tropical areas to compute monthly mean winds at these altitudes.

In the establishment of upper air stations, the most important need for aeronautical purposes, therefore, is to provide information over international air routes where jet streams may blow "on the nose (or tail)." It is suggested that priority should be given to the establishment of upper air stations over these routes at the departure and arrival aerodromes and at two intermediate stations situated up to 100/150 miles to port and starboard of track respectively, and not in line with the prevalent jet stream axis, as illustrated in Fig. 9.

This simple network probably would provide the necessary degree of accuracy in upper wind forecasts if, and only if, observations were made at fairly frequent intervals (not less than once every 6 hours), and the reports transmitted quickly to the terminal meteorological offices. Frequent observations will be required only during those seasons when jet streams are known to occur and in a large number of cases, stations could be closed down outside these periods and re-installed, possibly, for use on a more deserving sector. International collaboration appears necessary for maximum utilisation of equipment and personnel. There are obvious practical difficulties in establishing stations *C* and *D* over sectors such as Cairo/Bahrain, but with the present scarcity of high level wind measuring equipment and of personnel and funds, it would seem wiser to set up a few first-class key stations making frequent observations along significant routes, rather than hope vainly for implementation of a somewhat grandiose network. The latter requires action by various individual States to open a number of stations which would depend for their usefulness on other States opening stations.

Above the height of the temperate tropopause, and up to the height of the tropical tropopause, the normal latitudinal temperature gradient decreases owing to the continued decrease of temperature with height in the lower latitudes, and in consequence, the westerly winds decrease with height. It should be noted, however, that this reasoning does not always apply at higher latitudes.

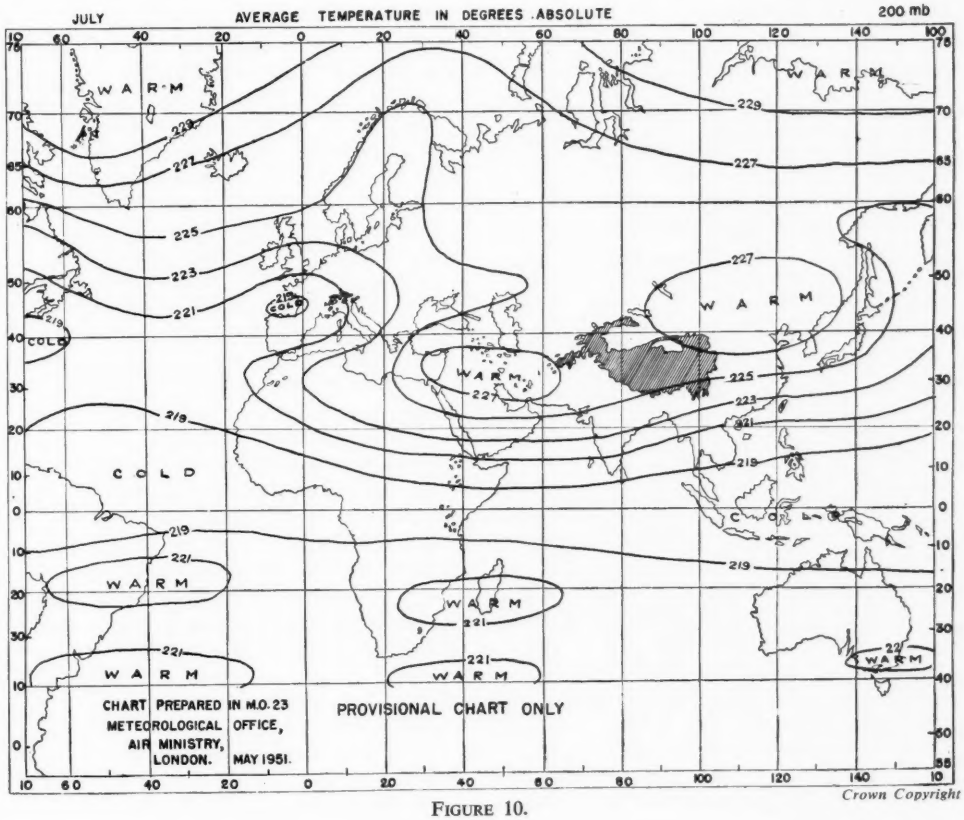

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FIGURE 10.

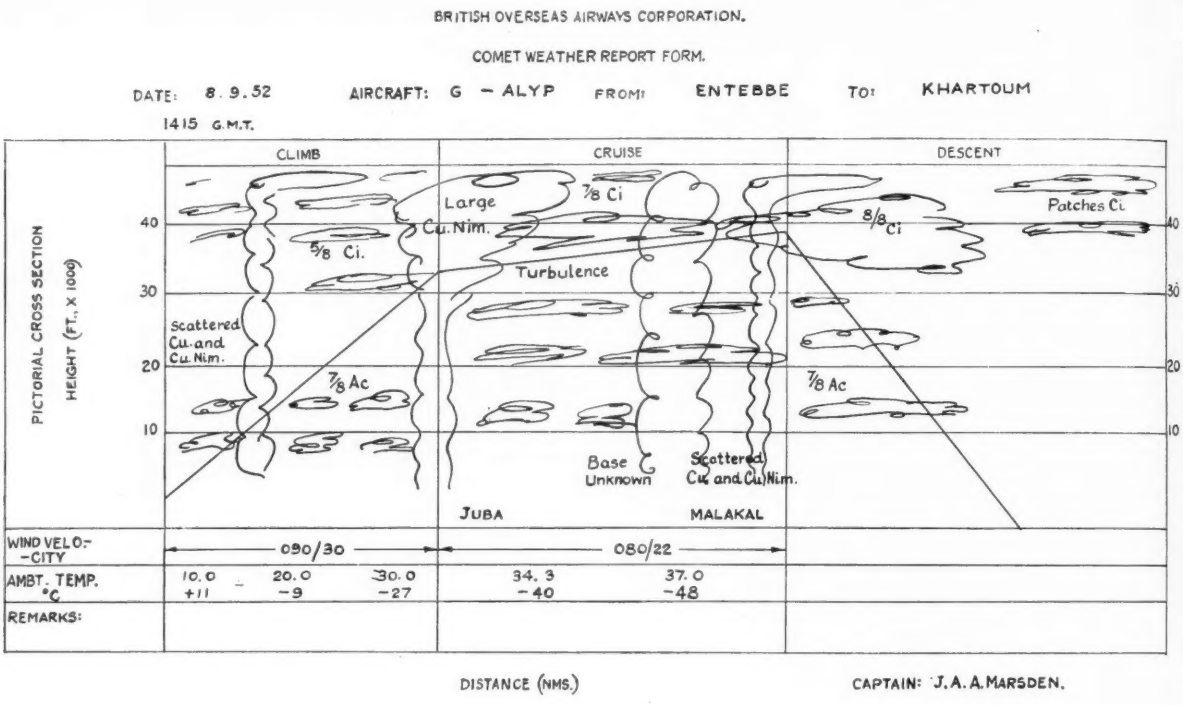


FIGURE 11.

In particular, temperature usually continues to fall in the stratosphere in high latitudes in winter, so that the strong westerlies over the North Atlantic in winter often show little or no decrease in the stratosphere and occasionally wind speed is at a maximum a few thousand feet above the tropopause. Usually the upper level temperature gradient is reversed before the tropical stratosphere is reached and the equator remains relatively cold above this level. This results in a continued decrease with height of the westerly wind and eventually, it is replaced by an easterly.

Thus easterly winds are found in temperate latitudes in summer at altitudes above about 70,000 ft. At the equator the prevailing upper winds are easterly throughout the year and these spread north and south with the movement of the sun. Thus in July, the easterlies extend to about 30°N. (the thermal equator), and there is a jet of 70 knots at 55,000 ft. (tropical tropopause) at about 15°N. The north/south movement of the easterlies takes place with great regularity and at 40,000 ft. they replace the westerlies fairly abruptly at Aden in mid-May and at Bahrain in mid-June. As a rough guide to the effect of wind and temperature on the range of the Comet I, over a 1,500 mile sector an increase of 7°C. in ambient temperature is equivalent to an increase of 4 knots in headwind, or a decrease in weight of one passenger plus baggage. It is only when abnormally high temperatures are accompanied by strong headwinds that the effect of temperature itself is really significant. These conditions have not been encountered so far and from theoretical considerations are unlikely. In fact, large variations of temperature are expected to occur only on sectors where the tropopause is sometimes below and sometimes above the cruising altitude, *e.g.* North Atlantic and Europe.

Charts of mean values and standard deviations of upper air temperatures over the world have been produced by the Air Ministry and Fig. 10 shows a provisional chart of mean temperature at 200 mbs. in July. As already mentioned, there is a tendency for temperature to become progressively warmer from equator to Poles above 200 mbs., corresponding to the decrease in the height of the tropopause. Temperatures actually measured on the Comet are in close agreement with the general charts and after one year's operation it is thought that the data will be sufficient to give a fairly accurate picture of temperature distribution over the various sectors. Mean monthly values of cruise temperature will probably be adequate for flight planning purposes, except over sectors where the tropopause intervenes.

Terminal Weather

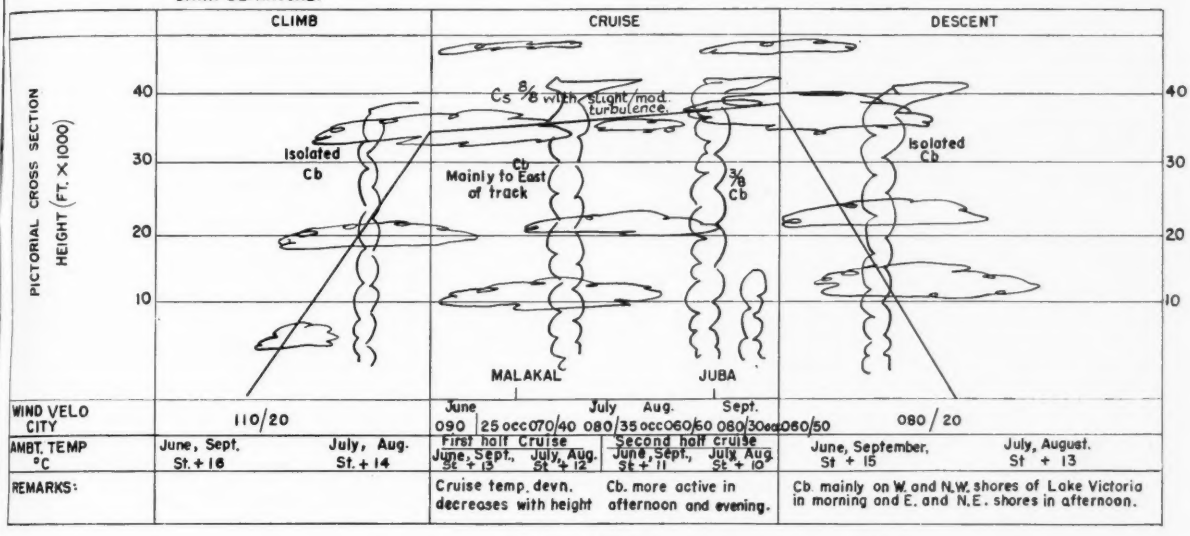
Usually by far the most important meteorological aspect of a Comet flight concerns the terminal weather. Alternates must be chosen which are not subject to deteriorations simultaneously with the main terminal, and detailed analysis of weather data is required to establish the risk of terminal and alternates being below limits at the same time. Frequently the data necessary for this analysis are not available and local opinion of a generalised nature can often be very misleading. The choice of alternates usually is restricted owing to considerations other than weather, *e.g.* runway length and bearing strength, landing aids, general facilities, and so on. For example, Brindisi and Bari are usually open

BRITISH OVERSEAS AIRWAYS CORPORATION

COMET WEATHER REPORT FORM

DATE: JUNE TO SEPTEMBER AIRCRAFT. FROM: KHARTOUM TO: ENTEBBE

DAWN DEPARTURE.



	CLIMB	CRUISE	DESCENT
WIND VELOCITY	110/20	June 090 | 25 occ 070/40 — July Aug. 080/35 occ 060/50 — Sept. 080/30 occ 060/50	080/20
AMBT. TEMP °C	June, Sept. St. + 16 — July, Aug. St. + 14	First half Cruise: June, Sept., St + 13 — July, Aug. St + 12 — Second half cruise: June, Sept., St + 11 — July, Aug. St + 10	June, September, St + 15 — July, August. St + 13
REMARKS:		Cruise temp. devn. decreases with height. Cb. more active in afternoon and evening.	Cb. mainly on W. and N.W. shores of Lake Victoria in morning and E. and N.E. shores in afternoon.

DISTANCE (NMS.) CAPTAIN:

FIGURE 12.

when Rome is closed, but at present are not suitable as alternates. The use of Nice and Malta as alternates to Rome involves additional fuel reserves and it is not known how often these two aerodromes have had below limits weather at the same time as Rome. It is possible, for example, that there might be an excessive cross wind on the only available runway at Nice if a winter depression results in below limits weather at Rome. Many problems of this nature are being analysed.

Irrespective of the choice of alternates, a constant watch on the terminal and alternate weather is the first essential of meteorological service for jet aircraft. There are two stages of the flight when the aircraft commander must be given up-to-date advice on terminal weather, *i.e.* just before reaching the critical point and just before beginning the descent. In the first case, a decision must be made whether or not to continue the flight or to return, and in the second case, it must be decided whether to descend to prepare for a landing at the terminal or whether to divert at altitude, bearing in mind the marked increase in fuel consumption at low altitudes. The decision naturally will often depend on the amount of fuel remaining at the time. If strong headwinds have reduced the fuel reserve, less "risk" will be taken than if the fuel reserve is higher than that originally planned for. Unfortunately, it is extremely difficult all over the world to forecast with precision the occurrence of below limits weather. Forecasting the time of onset and clearance of fog and low stratus, squall lines, thick dust haze, thunderstorms, and so on, can seldom be made with the necessary degree of accuracy, especially for the relatively low minima which are now in use. The distance a pilot is able to see lights along the runway (runway visual range), may be vastly different from the meteorological visibility, for example, at London Airport often it is twice as great at night, but there is as yet no means of forecasting R.V.R. (runway visual range). Forecasts are given only for the meteorological visibility.

It is recommended practice by I.C.A.O. that aerodrome weather forecasts should be prepared by the local meteorological office, or by the parent forecast office if no such office is situated on the aerodrome. These forecasts are distributed on a regular basis to those offices responsible for providing meteorological service to aircraft operating into the aerodrome. Departure meteorological offices usually accept these "tafots" without question, although they are required to brief the aircraft commander on possible changes in the synoptic situation and the effect these may have on the route and terminal forecasts. On many routes, especially outside Europe and the North Atlantic, terminal weather is based on local knowledge rather than on the synoptic situation and comparatively few forecasters possess the local knowledge of distant terminals. It is felt that neighbouring meteorological services, where possible, should interchange forecasters for periods of a few months for the purpose of providing them with necessary experience over the whole of the routes for which they are called upon to brief air crews.

Further difficulties arise because synoptic data are often not available over the whole route, or are out of date. Complete reliance is then placed on advice received from the terminal meteorological office. Such advisory messages may be issued many hours before the flight begins, to allow for communications delays and

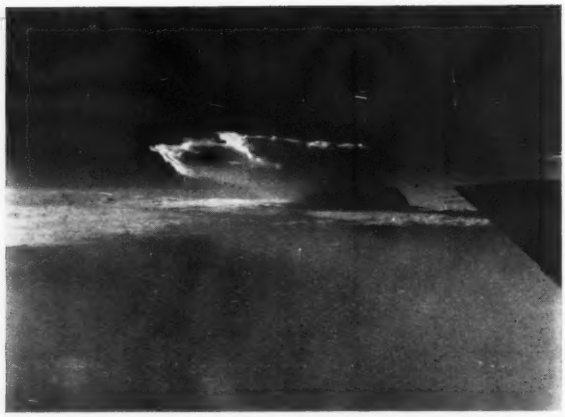


FIGURE 13. Taken on 5th July over the sector Bahrain-Karachi. The top of the Cumulo Nimbus is 41,500 ft. There is thick haze from the surface to the level of the medium cloud at 15,000 ft. The wind at 40,000 ft. is clearly from the east.

FIGURE 14. Cloud over the Himalayas. Mount Everest is seen on the left hand side of the photograph which was taken from a height of 36,500 ft. from 90 miles W.S.W. of Everest. Cumulo Nimbus in the background extends to 40,000 ft. "Small" Cu to 16,000 ft. is shown in the foreground.

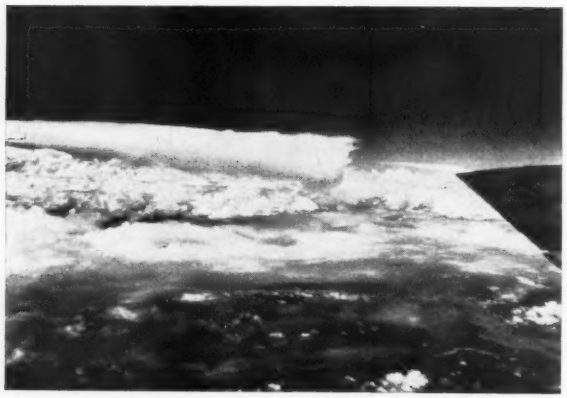


FIGURE 15. Aircraft flying from Delhi to Calcutta. The photograph shows an anvil from Cumulo Nimbus at 36,000 ft. which is at least 25 miles long just to the N.E. of Patna.

for coding, de-coding and co-ordination into the general forecast at the departure office. Thus there are three requirements:—

(*a*) Terminal forecasts to be prepared by the local meteorological office and disseminated to all users and to be kept constantly under review and amended as necessary. In practice this is being done, although the amendment system often is inefficient and long delays are experienced in transmission.

(*b*) Forecasters should have all the necessary basic weather data to permit them to interpret the terminal forecast in relation to the synoptic situation.

(*c*) Forecasters should have first hand experience of weather at terminal aerodromes so that they may be able to interpret better the terminal forecast and give advice on possible changes.

Although synoptic data from a limited network of stations over a fairly wide area are necessary as a basis for forecasting a few hours ahead, a denser network of stations over a smaller radius is required for forecasting a short time ahead. Radar methods for detecting thunderstorms within a certain radius of aerodromes might possibly be used more profitably than a dense network of stations at certain aerodromes in certain seasons. There is now a requirement for forecasts to be given for a period of minutes, *e.g.* when a pilot is approaching a terminal aerodrome he requires to know when the approach lights or markers will be visible and when nearing his critical height, he requires to know the runway visual range. Thereafter, until the aircraft is brought to rest, he requires to see the lights or visual markings at a minimum distance, equal approximately to the distance travelled by the aircraft in three seconds (assuming constant speed), plus due allowance for cockpit cut-off, turbulence, heavy rain, etc. Thus, just before reaching critical height (assuming he has established visual contact with the ground or approach lights), the pilot requires an assurance that he will not "run out" of visibility, *i.e.* a minimum segment of ground must always be in view. The requirement is, therefore, for an accurate spot observation of R.V.R. and a short period trend.

In Flight

As in the other phases of meteorological service, the main difficulties experienced in flight are due to inadequate communications. Arrangements are made for an appraisal of terminal and alternate weather in the form of the latest actuals and forecast for E.T.A. (Estimated Time of Arrival) to be sent to the aircraft just before reaching the critical point and just before beginning descent. However, these messages, especially about alternate weather, are never quite up-to-date and at times communications difficulties are such that they are not received by the aircraft at the times required. At the present time, it is necessary to supplement this information by intercepting sub-area broadcasts. On all Comet flights, individual flight meteorological watch is observed by the various meteorological services and for

any particular sector it is usually shared between the departure and terminal meteorological offices. Superimposed on this is the so-called Area Watch whereby certain meteorological offices, designated meteorological watch offices, are responsible for issuing warnings of bad weather conditions affecting, or likely to affect, their associated F.I.R.s (Flight Information Regions) or other designated areas. Experience so far indicates that warning messages of little or no operational significance are issued from time to time and are a hindrance rather than a help to operations. In addition, communications difficulties aggravate the situation. For example, a forecast warning of rising dust reducing visibililty to 300 yards over an area including the terminal and alternates might be issued by a certain centre. This warning is sent to neighbouring F.I.R.s and, some time after the time of origin of the message, may reach the aircraft in the early stages of the flight. Difficulties in communications might prevent direct contact with the terminal to obtain later information and the aircraft may turn back unnecessarily, especially as there is a tendency for meteorological offices to delay the issue of cancellation messages.

In addition to meteorological flight watch, a Corporation flight watch is exercised by specially trained station officers. Watch at the arrival aerodrome is maintained throughout the flight and at the departure aerodrome until E.T.A. critical point, plus 15 minutes. The station officers maintain a close liaison with the forecaster undertaking meteorological watch and by this means advice on weather of operational significance is sent to the aircraft as far as the communications system will allow.

Meteorological conditions experienced in flight are recorded in duplicate on special forms printed by the Corporation, separate forms being used for each sector. One of the forms is handed into the terminal meteorological office on arrival and if necessary, is amplified by personal debriefing of the aircraft commander. A typical form is shown in Fig. 11. The duplicate forms, together with the various forecasts issued to a service, remain on the aircraft until it returns to London, when they are despatched to Head Office. From an analysis of such reports, forms showing the weather experienced over individual sectors on a seasonal basis are being constructed. With the assistance of the various meteorological services along the routes, it is intended to produce a weather guide with particular reference to route and terminal weather of operational significance. An example of a seasonal weather diagram is given in Fig. 12.

Although ambient air temperatures are obtained with a high degree of accuracy, wind finding is much more difficult in a fast moving aircraft with limited navigational aids available, as navigators well appreciate. However, fairly consistant results have been obtained, especially over the tropical sectors where the winds are reasonably constant, and mean seasonal values deduced from these observations are in general agreement with the relatively small amount of information available from radar and pilot balloon observations. Over most of the tropical sectors it is thought that meteorological services will not be able to improve very much on the seasonal data so obtained and forecast service will be restricted to take-off and landing conditions, together with significant changes in route weather from seasonal, if such information is available. Apart from winds and temperatures, route weather is of significance only when severe icing, or severe turbulence, is likely to be encountered, with the possible exception of sectors where, for want of a better aid, astro navigation is used, when extensive sheets of cirro stratus at or above cruising altitude would be significant.

Since very little flying occurs outside the troposphere, it is not surprising that Comet flying not infrequently is in, near, or just below, extensive cloud systems. Often,

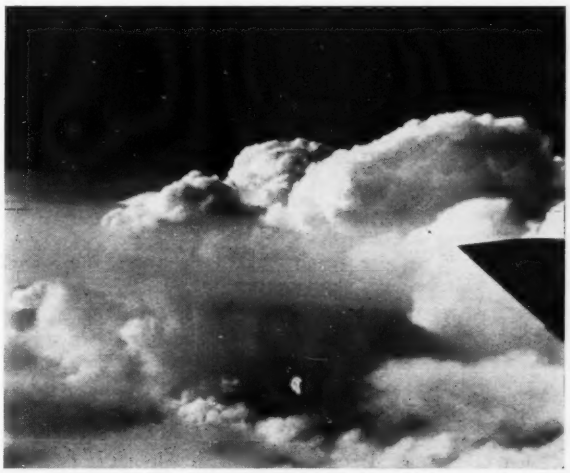


FIGURE 16. Taken over the Indian Ocean flying from Rangoon to Colombo at 0730 hours (local time), the photograph shows heavy Cumulus still developing. The aircraft was at 40,000 ft. and the Cumulus tops measured 45,000 ft. There is a thin veil of Cirrostratus at 37,000 ft. Severe turbulence was experienced when the aircraft flew through the Cumulus.

FIGURE 17. Striking narrow line of congested Cumulus 75 miles long and 5 miles wide, about 50 miles from the aircraft. Base of the cloud is 10,000 ft. and tops 15/20,000 ft. Some of the detail is masked by Cirrostratus. This cloud was of no significance to the Comet but might well have proved troublesome to an aircraft flying at 15,000 ft.

however, the Comet is above the weather and "solid" large Cumulus and Cumulo Nimbus cloud with main tops at 20,000 to 25,000 ft., very significant to other present-day types of aircraft, may be reported by Comet captains as "small Cu. and Strato Cu." Nevertheless, Cumulo Nimbus cloud above 45,000 ft. is a fairly common occurrence in certain seasons and it is not uncommon in the Mediterranean, especially over Greece and Crete, and over Northern Italy in summer. It can usually be avoided, but when flying through the I.T.C.Z. in Africa, or through active monsoonal disturbances farther east, it is sometimes embedded in thick Cirrostratus and little or no warning may be received of its presence. It is possible that search radar fitted to the aircraft might prove useful in detecting Cumulo Nimbus cloud of this nature. Many cloud photographs have been taken from the Comet and a few are reproduced in Figs. 13, 14, 15, 16 and 17; these were all taken on behalf of the Meteorological Office by the author on the first Comet development flight to Tokyo in July 1952.

Figure 18 illustrates a possible formation of wide spread tropical Cirrus at the March equinox suggested by Durst in a paper of the Meteorological Research Committee.

Meteorological services are unable to forecast cloud amounts and cloud tops very accurately at Comet levels but, apart from the special cases already mentioned, this is relatively unimportant. Turbulence experienced in Cumulo Nimbus cloud at Comet speeds and altitudes is of approximately the same intensity as at lower altitudes with present piston-engined aircraft and the rule is to avoid Cumulo Nimbus cloud if possible. Hail, lightning, and icing have been observed at 38,000 ft. so that all significant weather experienced at altitudes below 25,000 ft. may also be experienced at least up to 40,000 ft. Icing at these altitudes, however, is rare and of minor significance. De-icing problems are likely to arise only during descent and even then are unlikely to be serious. So far, comparatively little clear air turbulence has been observed and has mainly been slight "cobblestones," but care is taken in areas where severe clear air turbulence is likely to occur, *e.g.* near the tropopause in well defined frontal zones. Moderate and severe clear air turbulence has been encountered, in fact, in northwesterly jet streams over the sector Rome/London.

Present and Future Problems

Summarising briefly, present requirements demand:

(1) A more detailed knowledge of upper winds over the world for evaluating mean equivalent headwinds for planning purposes,

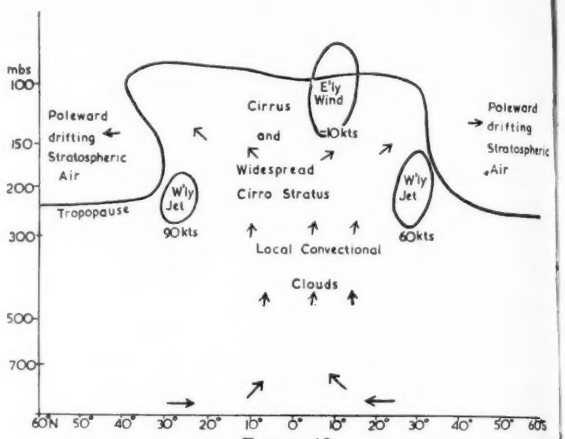


FIGURE 18. *Crown Copyright*

(2) Improved technique for forecasting upper winds at 200 mbs. in temperate latitudes,
(3) Further research into tropopause behaviour,
(4) Accurate terminal forecasts, especially for short periods ahead,
(5) Efficient communications for (*a*) exchange of meteorological information between meteorological services along air routes, (*b*) air/ground exchanges between pilot and ground agencies.

Future Requirements must take into consideration:—

(*a*) new routes and still higher altitudes,
(*b*) increased range and speed of aircraft,
(*c*) exclusive use of R/T for air/ground communications,
(*d*) reduction of crew members in the cockpit.

Thus the existing heavy demands on the aeronautical meteorological services are unlikely to decrease in the foreseeable future and they will continue to play a vital part in the safety and economic factors of civil air operations.

ACKNOWLEDGMENTS

The author is indebted to the Director of the Meteorological Office and to the Controller, H.M. Stationery Office, for permission to reproduce Figs. 3, 5, 6, 7, 8 and 18; Fig 3 is reproduced from Geophysical Memoir No. 85, Figs. 5-8 inclusive from Professional Note No. 107 and Fig. 18 from *Meteorological Magazine*, March 1953. He also thanks Pan American Airways for permission to reproduce Fig. 4.

He also acknowledges permission to publish the paper from the British Overseas Airways Corporation and to reproduce some Corporation charts. Any opinions expressed in the paper are the author's and not necessarily those of the Corporation.

The Development of 4,000 lb./in.^{2} Hydraulic Systems*

by

G. ORLOFF
(*British Messier Ltd.*)

1. Introduction

Looking back to the early days of aircraft hydraulic systems, a steady upward trend in the operating pressures used can be observed.

One of the reasons for this increase is weight saving, which has become of particular importance in recent years on account of the increased complexity and power demand of the modern hydraulic systems.

The trend in the direction of higher pressures has been necessarily gradual because of the lack of knowledge and experience in this field, and prudence has precluded the adoption of large steps.

Another step has been achieved in Great Britain by successfully raising the working pressure to 4,000 lb./in.^{2} on several modern aircraft.

2. The Case for High Pressures

It is well known that since the early days of hydraulics on aircraft, the power demand of services and the number of these, have increased enormously and resulted in a continued increase in working pressures: in England from 1935 to 1940 the operating pressures had risen from 800 lb./in.^{2} to 2,500 lb./in.^{2} and they remained at this level until 1948. In America the corresponding rise was from about 800 lb./in.^{2} to 3,000 lb./in.^{2} and this value still remains the normally accepted pressure on most American aircraft. France, since 1945, has produced systems working at 3,500 lb./in.^{2}, and since 1947 Great Britain has introduced a system working at 4,000 lb./in.^{2} Today at least five aircraft are flying successfully in this country with this system pressure; four are military machines with complicated multi-service systems and one is the Bristol Britannia with a hydraulic power supply of approximately 40 f.h.p.

The available information has been plotted in Fig. 1, which shows the trend towards higher pressures†.

The systems under consideration are the ones used for undercarriage retraction, power steering, lowering of flaps, operation of air brakes, and so on; they do not include services such as propeller pitch control gear, which are operated by engine oil from the engine, or pilot-energised brake systems on light aircraft where a balance must be struck between useful work done and the work done in straining the pressure lines and fluid.

There are several attractive reasons for raising the pressure in systems, namely weight saving, reduction of bulk and therefore of vulnerability, and increased stiffness for flying controls.

At one time some controversy existed on the question of weight saving at increased pressures.

In actual fact there cannot be any doubt today that within the practical limits of pressures, jack lengths an pipe sizes, the balance is in favour of the higher pressures, at any rate, up to a value of 4,000 lb./in.^{2}. Probably the best illustration of weight saving is by choosing a specific case, and the results of a typical analysis are given for system pressures of up to 10,000 lb./in.^{2}.

The system considered is shown in Fig. 2, in which an overall distance of 100 ft. has been taken between the reservoir and actuator, and where most of the components have been grouped in the first 30 ft. It should be noted that the pipe lengths in this case have purposely been made excessive, making, as will be seen, the conditions pessimistic for high pressures.

Stresses in all pipe sizes have been kept as constant as standard pipe thicknesses would allow, varying from approximately 8,000 lb./in.^{2} to 9,500 lb./in.^{2} for $\frac{3}{16}$ in. diameter pipes, to about 15,000 lb./in.^{2} for $\frac{1}{2}$ in. diameter pipes.

In calculating pipe losses, the more pessimistic case of jack closing was taken, and the allowable loss was assumed to be equal to the difference between the working pressure of the jack and the cut-out pressure of the system.

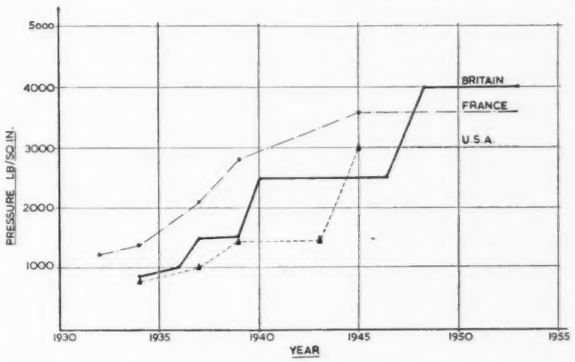


FIGURE 1. Growth of system pressure.

†Based on *Developments in High Pressure Hydraulic Systems* by H. G. Conway.

*A Section Lecture given before the Society on 3rd Nov. 1953.

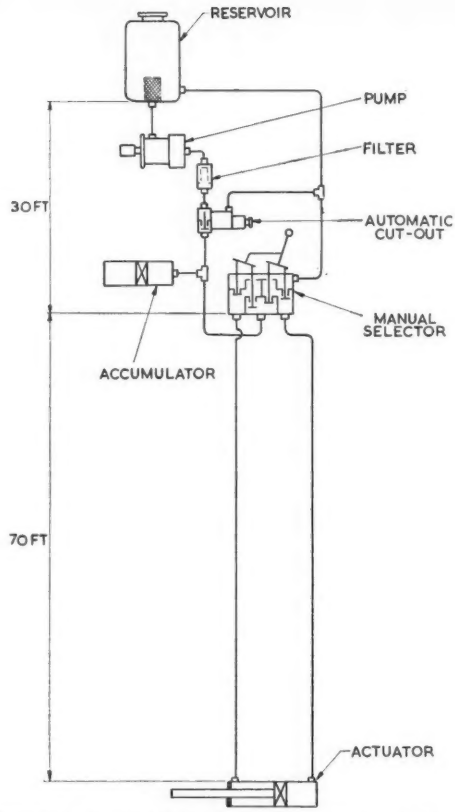


FIGURE 2. Typical hydraulic system for weight analysis.

The losses were estimated for a temperature of 0°C., using the kinematic viscosity of fluid D.T.D.585.

In estimating pressure drops through the components, the effect of viscosity has been neglected, since the losses are mainly due to turbulence.

The useful volume of the accumulator was assumed to be equal to 1·5 times the pump delivery in cu. in./sec., and its inflation pressure was made equal to the maximum working pressure of the jack. The shape of accumulator was cylindrical, with a stroke/diameter ratio varying between 3 and 5.

The weights of the pump, filter, cut-out and selector have been taken as proportional to the fluid horsepower of the pump and thus remained sensibly constant.

In calculating the weight of the reservoir and of the fluid in it, it was assumed that 25 per cent. excess volume was carried over the jack swept volume and that the reservoir size was 50 per cent. in excess of the total volume.

Other assumptions were:

pump cut-in pressure	$=7/8\ P$ where P is the working pressure
jack useful operating pressure	$=0{\cdot}8P$.
jack thrust load	$=32{,}000$ lb.
jack strut strength	$=2\times 32{,}000=64{,}000$ lb.
extension time of jack	$=8$ secs.
basic size of jack at 4,000 lb./in^2	$=3$ in. bore $\times$ 11 in. str. and 6·4 lb. weight

The results of individual analyses are shown in Figs. 3, 4, 5 and 6, which illustrate how the weights of the jack, accumulator, tank and pipes vary with system pressure.

At this point one feels diffident about showing the overall result without saying that there is no intention of claiming that the 4,000 lb./in.^{2} system is the lightest: let it be accepted that the assumptions were made in good faith without any ulterior motive and that the result of the curve shown in Fig. 7 giving the total system weight-pressure relationship is accidental.

The general inference from the graphs in Figs. 3 to 6, is that the main weight saving at high pressures occurs in jack, tank and fluid, but that there is a penalty with pipes and accumulator.

One practical advantage of high pressures is the possibility of making full use of high grade steels in jacks and cylindrical components of relatively small diameter: since the weight of cylinders is inversely proportional to the working stress in them, this allows reasonable wall thicknesses to be maintained without any weight penalty and avoids the necessity of adopting light alloy materials which have been found undesirable on account of their poor fatigue properties.

3. The Case against High Pressures

On the other side of the "balance sheet" the difficulties in using higher pressures are principally as follows:

(*a*) Difficulties in sealing of valves.
(*b*) Reduced life of flexible packings.
(*c*) The lack of knowledge regarding friction of these at high pressures.
(*d*) The danger of hydraulic surge.
(*e*) The strut strength of jacks.
(*f*) The possibility of increased fire risk.

Precautions were taken during the design stages of the system to safeguard it against difficulties of valve sealing, hydraulic surge and jack strut strength. Endurance testing of all components was done to ascertain that the life of flexible packings was adequate, and direct experimental work was undertaken to determine their friction and to evaluate the fire hazard of the system. The steps taken and the results obtained are outlined briefly.

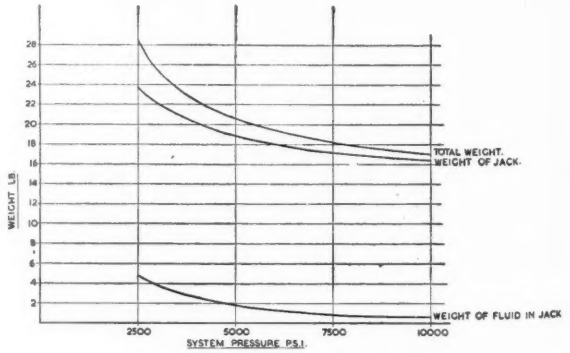


FIGURE 3. Variation in jack weight,

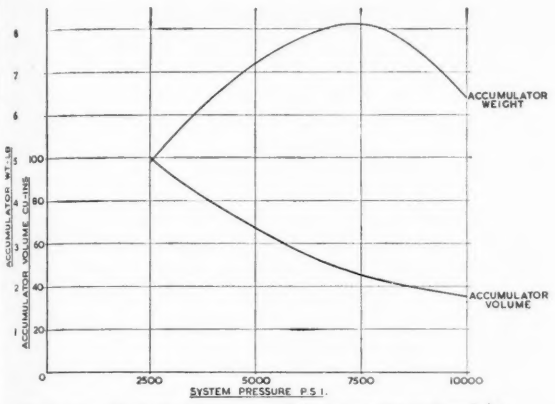


FIGURE 4. Variation in accumulator capacity and weight.

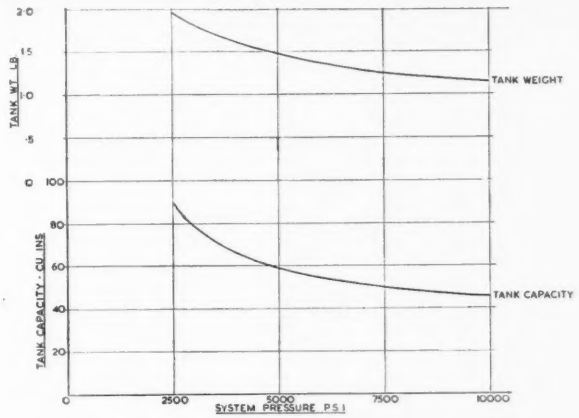


FIGURE 5. Variation in tank capacity and weight.

4. General Conception of Systems

Having agreed, in 1947, that an increase of working pressure was desirable, a decision had to be made as to the step that could safely be taken: statistically, previous steps were approximately in the ratio of 1·6 and hence a rise from 2,500 lb./in.² to 4,000 lb./in.² appeared reasonable. Furthermore, the work done in the U.S.A. at 3,000 lb./in.² and the more limited development in France at 3,500 lb./in.² (250 kg./cm.²) were encouraging, and there was evidence that the normal A.G.S. pipe connections would be cleared, together with pipes having slightly greater thicknesses, for working pressures of up to 4,500 lb./in.² in the range of sizes considered.

A maximum normal system pressure of 4,000 lb./in.² was therefore chosen as offering the best compromise between weight saving and development.

To formulate the design policy of the 4,000 lb./in.² system, a review was made of previous hydraulic experience at 2,500 lb./in.² and at pressures in excess of this gained from incidental laboratory experiments, with the following results:

The pump—The chosen pressure eliminated all units except the positive displacement plunger type. The demand at the time was for powers of 8 to 40 f.h.p. within a speed range of 3,200 r.p.m. to 3,800 r.p.m., and since the larger power demand was associated with four-engined aircraft where, for reasons of safety, it was desirable to install one pump per engine, a basic pump power of between 8 and 10 f.h.p. was chosen, corresponding to a delivery of 15 cu. in./sec. at 3,500 r.p.m.

Governing of pressure—Since multi-engined aircraft were foremost in mind for the high pressure system, implying multiple pump power supply, it was decided, on the score of weight and simplicity, to govern the system pressure by a single automatic cut-out, and to use constant displacement pumps. The cut-in value of the automatic cut-out was to be between 80 per cent. and 90 per cent. of the working pressure, the exact value depending upon the detail design of this unit.

Valves in general—It was considered that a hermetic system was necessary and, ideally, one which caused the cut-out to operate only when a demand was given to a service; the stable poppet valve shown in Fig. 8 was chosen as giving the nearest approach to this ideal at high pressures, consistent with minimum manufacturing difficulties. In order to reduce the hydraulic surge, which is inherent to this type of valve, it was either to be hydraulically damped, or its speed of movement suitably controlled.

Slide valves were accepted in special cases, such as for nosewheel steering, since when not in use, they could be isolated from the main system by an input poppet valve selector.

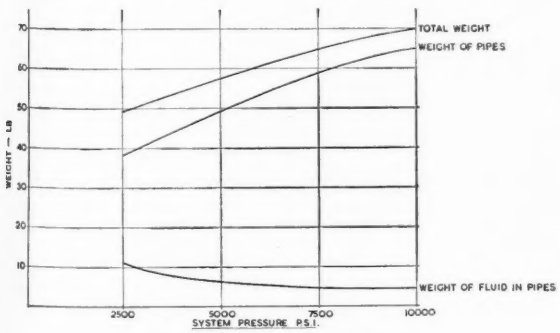


FIGURE 6. Variation in pipe weight.

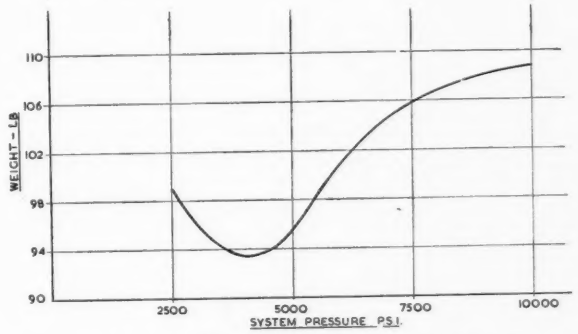


FIGURE 7. Variation of total weight of hydraulic system.

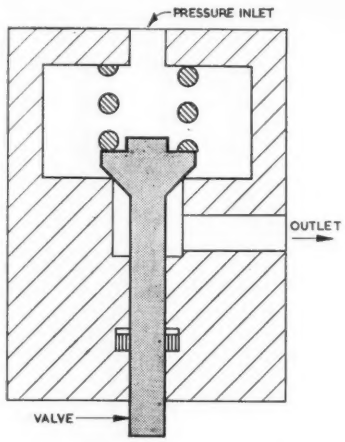


FIGURE 8. Stable poppet valve.

Control valves—Comparisons were made between multi-selector systems, *i.e.* systems combining each actuator with its own selector, and centralised systems, in which a single master control valve handled the full flow demand for a complete service, irrespective of the number of actuators involved. The centralised system was chosen because of weight and simplicity.

Emergency power—Although hand pump emergency was adequate for relatively small systems, the problem had to be reviewed for systems requiring normal powers in excess of 20 f.h.p. The choice lay between stored energy systems and continuous systems or, in practice, between an air bottle system and an electrically-driven auxiliary pump. The balance in favour of the latter was brought about by requirements for repeated emergency duty cycles of certain services, which made any stored air emergency system too heavy, and by the attraction of a uniform system allowing instant reversion to normal circuit conditions.

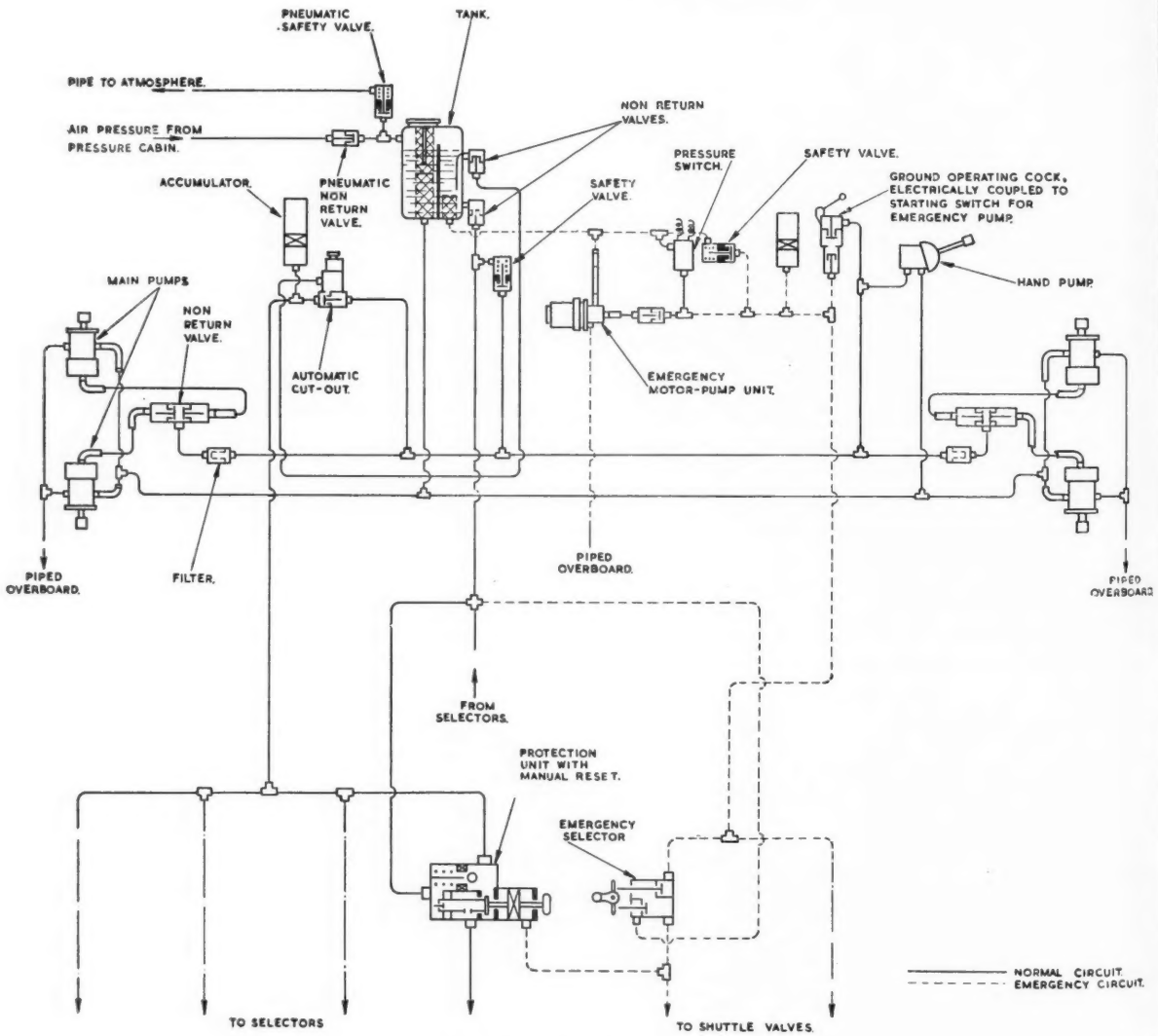


FIGURE 9. Basic line diagram.

Emergency system governing and control—The pump was to draw fluid from a portion of the normal hydraulic reservoir, maintained full automatically by the normal return flow of fluid from the services.

The governing of pressure in the emergency system was to be by means of a pressure switch cutting off the electric current to the electric motor at a pressure of 4,000 lb./in.² and automatically closing the circuit when the pressure fell to 3,500 lb./in.². A smoothing accumulator and safety valve were considered necessary to give added capacity and increased protection respectively; the input into the service jacks was to be done through shuttle valves in the normal manner and selection effected by a 3-way selector suitably linked to an emergency switch.

An automatic device called a protection unit, was to be devised to permit the emergency signal to over-ride the normal control of any service and isolate it from the remainder of the system, without causing a general loss in pressure.

The basic line diagram shown in Fig. 9 is a typical example of a system conforming to these requirements and has formed the basis of most 4,000 lb./in.² hydraulic systems flying in this country.

Main and thermal relief valves—For main relief valves there was every indication that the U.M.C. type of stable inverted unit would be satisfactory. Thermal relief valves, on the other hand had been troublesome, mainly on account of their sensitivity to hydraulic surge; it was decided to develop a really effective thermal relief valve which would only relieve under slow rates of pressure rise, such as are met during thermal expansion, but which would be insensitive to hydraulic surges of reasonable amplitude.

Hydraulic jacks—The broad precautions that were to be taken in the design of actuators were to use steel cylinders with built-in filters and to avoid long slender units, by requesting the aircraft manufacturers to choose attachment points such as to give, wherever possible, length to diameter ratios not greater than 10.

Accumulators—Cylindrical steel accumulators were chosen with light alloy separator pistons, similar to previously well established practice.

Rubber rings—Previous existing experience had shown that the normal concentric hard and soft rubber rings were adequate for dynamic packings and that static seals of 70 Shore hardness rubber were satisfactory.

5. Design Features and Development of Individual Items

The work done since 1947, in the laboratory, amounts to approximately 180,000 man-hours, the greater part of which was connected with the development of individual components.

In addition to the usual functional and strength testing, endurance testing was done, in certain cases exceeding 200,000 cycles on a given component, to assess the useful life of the units. In the early days these experiments also constituted fatigue testing: this, however, has recently been accelerated by subjecting the specimens to separate impulse testing at 5,000 lb./in.².

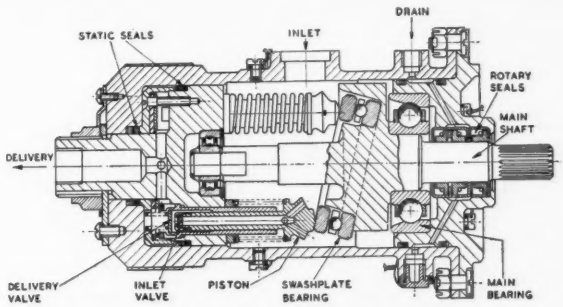


FIGURE 10. Fully developed pump arrangement.

A few examples of component development have been given to illustrate the problems encountered.

5.1. POWER PUMP

As could be expected, the power pump was the first item to be designed and developed.

The current unit is shown in Fig. 10 and is basically a seven-cylinder rotating swashplate pump in which the fluid is drawn from the casing, through the hollow plungers and into the pump cylinders, after passing automatic inlet valves retained at the end of the plungers by means of a crimped cage. The delivery of the fluid under pressure is effected past flat steel delivery valves into a collector annulus, and out through the delivery connection forming part of the cylinder block.

The difficulties encountered during the development of this pump were connected partly with the life of the main bearing, and partly with the design of the piston heads, bearing on the swashplate, but there were no troubles which could be directly ascribed to the high pressure.

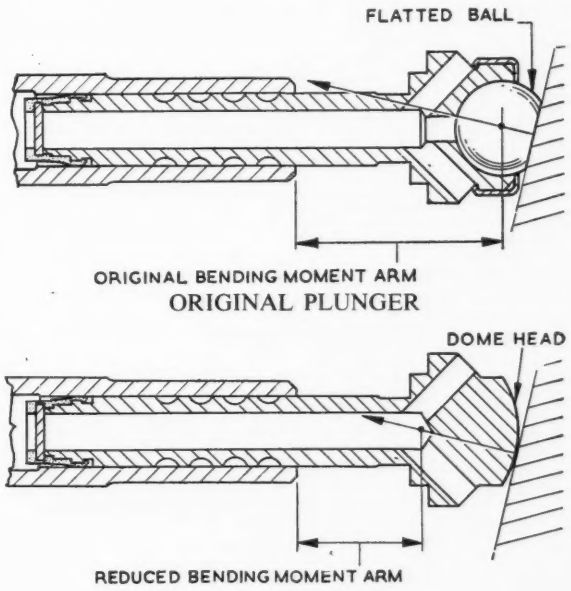


FIGURE 11. Modified plunger.

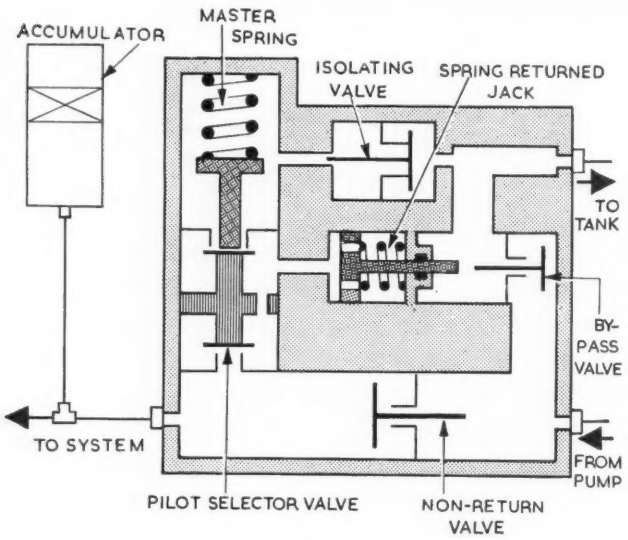


FIGURE 12. Diagram of original automatic cut-out.

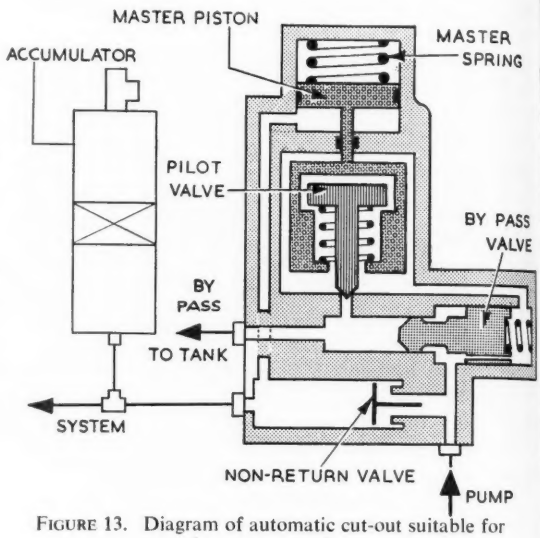


FIGURE 13. Diagram of automatic cut-out suitable for large power units.

By changing the main bearing from a taper roller type to an angular contact ball race of robust design, the life of this item was made adequate for at least two consecutive type tests.

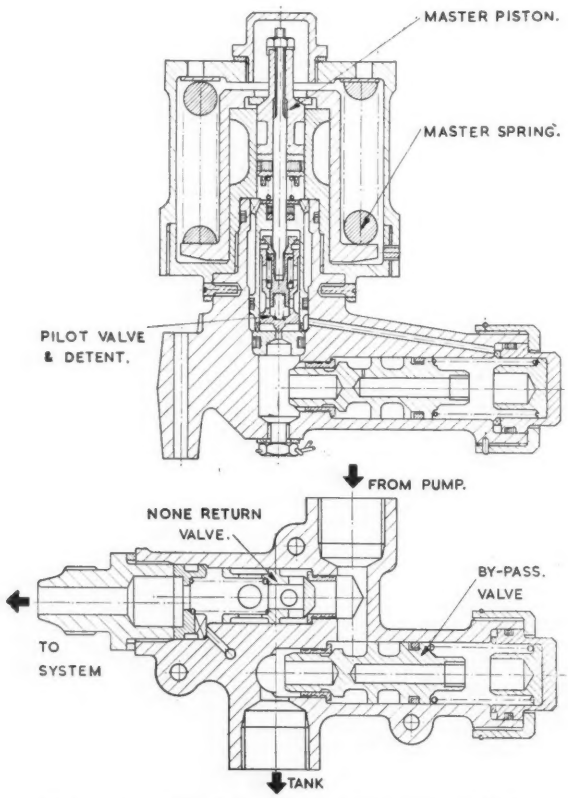


FIGURE 14. General arrangement of cut-out suitable for large power inputs.

The other difficulty consisted of occasional seizure of the plungers and cylinders. Investigations into plunger and cylinder fits and surface finishes did not provide any explanation and the design of the plunger was changed to the one shown in Fig. 11, in which the flatted ball was replaced by a dome head of large radius. This gave the dual advantage of reducing the tilting moment induced by the swashplate and of inducing rotation of the plungers, thus ensuring a more even distribution of the lubricating oil film.

The modified pump, after a few further detail improvements, completed a test lasting 2,000 hours. Today these pumps are fitted to four different types of aircraft and are in constant use in the mechanical laboratory as standard pressure sources where they have a very adequate life.

5.2. AUTOMATIC CUT-OUT

The automatic cut-out was probably the most interesting development item since its conception underwent very severe changes.

The first principle to be adopted is shown in Fig. 12, where the pressure signal acted upon a spring-loaded over-balanced pilot selector valve, which admitted pressure to, or vented, a small spring-returned jack operating the main off-loading valve. This scheme had in the past been used successfully at lower pressures in systems having an input of approximately 8 to 10 f.h.p., and it was equally successful at 4,000 lb./in.^{2} with the same power input, notwithstanding the rather critical setting requirements of the clearances between the valve seats of the pilot selector valve. At input powers of 30 to 35 f.h.p., however, the unit became excessively noisy, and pressure recordings taken downstream of the cut-out occasionally showed momentary surges of 6,500 lb./in.^{2}. Attempts to damp the opening and closure of the main off-loading valve resulted in instability, due to hydraulic interactions at the common tank return. After

some futile attempts to isolate the pilot tank valve from the main return flow, the scheme was abandoned in favour of the principle shown in Fig. 13.

The new principle adopted for high power inputs consisted essentially of a pressure measuring device composed of a spring loaded plunger, which acted upon a pilot valve in such a manner as to open or close the latter, depending upon the pressure of the system, and of a main valve responding to the flow signal in such a manner as to follow the pilot valve but at a larger amplitude: with the pilot valve closed, the pressure acting upon the valve would close the latter, but when the pilot valve opened the drop of pressure across the main valve annular area would overcome the pressure forces and the valve would move into the open position. In actual practice a mechanical detent was provided between the master piston and pilot valve to avoid any intermediate position, and the follow up valve was designed to have an extension entering within the valve seat, which was drilled to give a pseudo linear pressure/time curve. The design of this cut-out is given in Fig. 14 where the various elements previously shown can be readily recognised.

The development of this unit presented no serious difficulties and most of the experimental work was directed to improve the pilot valve orifice and to obtain an optimum hole pattern in the extension of the main valve. Fig. 15 shows the pressure/time curves obtained by cathode-ray measurements at the inlet, system and tank connections of the cut-out. This unit is silent in operation for powers ranging from 6 to 40 f.h.p. at a system pressure of 4,000 lb./in.²

5.3. SELECTORS

There are mainly three basic types of selectors used in the current system: these are manually-operated selectors, mainly used for emergency purposes, motor-driven selectors with two positions used in normal services, such as for undercarriage retraction, bomb doors, and so on, and solenoid-operated selectors, with a third neutral closed position used where infinitely variable control of the jack is necessary.

Only the development of the motor-driven selector will be discussed, since it is the more intricate unit and required more extensive testing.

An electric motor drive was adopted on the grounds that it was more efficient and lighter than solenoids for the operation of pilot poppet valves of a reasonable size.

The principle of the selector is given in Fig. 16, where an electrically-operated screw actuator acts upon a cam, shaped with two sloping faces, which in turn depress the pilot valves of a three-way selector. The cam was provided with fingers moving a double pole switch which reversed the electric circuit to the split field

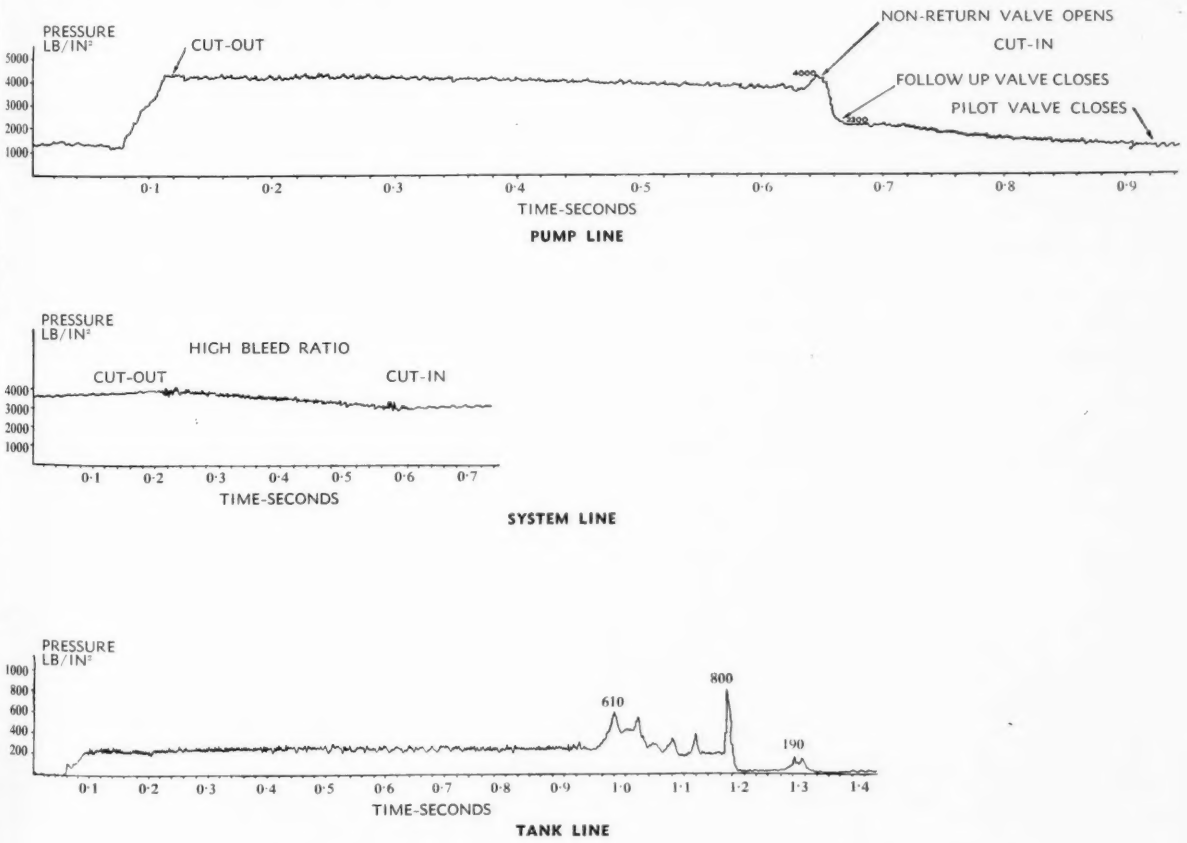


FIGURE 15. C.R.O. pressure traces taken at the cut-out connections.

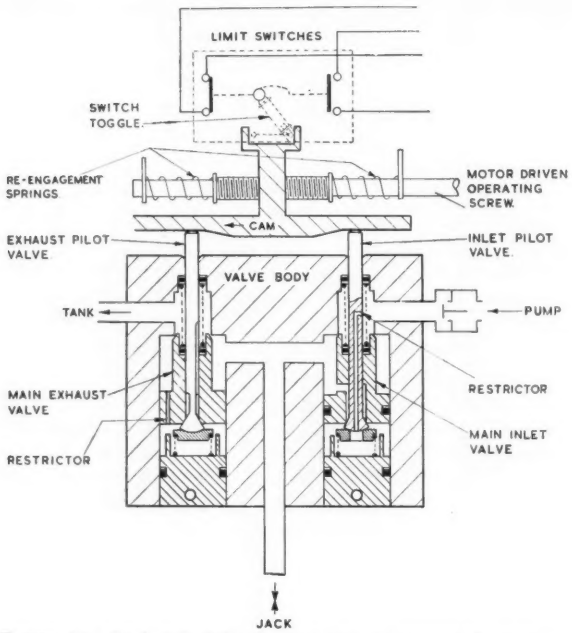


FIGURE 16. Basic principle of a 3-way motor operated selector.

motor, upon reaching the extremities of the actuator screw thread; the cam was allowed to run off the screw thread at these extremities, thus avoiding the necessity of having magnetic brakes within the motor. Subsequent re-engagement was secured by springs exerting a thrust upon the cam in the direction of the screw.

The admission valve, when free, was seated by a return spring, also acting on the pilot valve, and by a hydraulic force due to the pressure acting upon the annular valve area, corresponding to the one exposed to the back pressure in the jack line. When the cam was moved to open the pilot valve the pressure drop obtained through the restriction in the pilot valve stem caused the main valve to follow in the open direction.

The exhaust valve, when free, was seated by a spring force and by the system pressure acting upon the pilot and main valve seat areas. Movement of the pilot valve into the open direction induced a pressure drop across the main valve, causing it to lift against the hydrostatic seating forces.

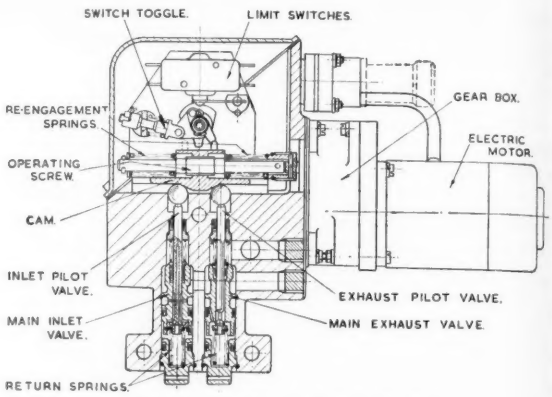


FIGURE 17. 3-way motor selector.

The general arrangement of the current three-way selector is shown in Fig. 17, where it can be noticed that the motor operates the master screw through a small gearbox.

Originally it was intended to operate a fine pitch master screw directly from the motor, but early experiments showed such poor overall efficiency that the scheme was modified to have a gearbox and a four start thread at the actuator screw. No further trouble was experienced during normal functioning tests, but reverse flow tests revealed a tendency for the input main valve to close, and this was overcome by introducing an abutment which limited the relative movement between the pilot and follow up valve.

Further difficulties were experienced during endurance testing when after approximately 5,000 operations, it was found that locking occurred between the actuator screw threads during re-engagement of the cam. This was overcome by choosing harder materials and increasing the strength of the return springs. Further corrections were found necessary mainly in connection with the detail design of the reversing switch and by the time this type of selector was fully developed it is estimated that several units had undergone approximately 60,000 operations.

5.4. HYDRAULIC JACKS

Figure 18 shows a typical jack suitable for a pressure of 4,000 lb./in.^{2}. The main difficulties met in such

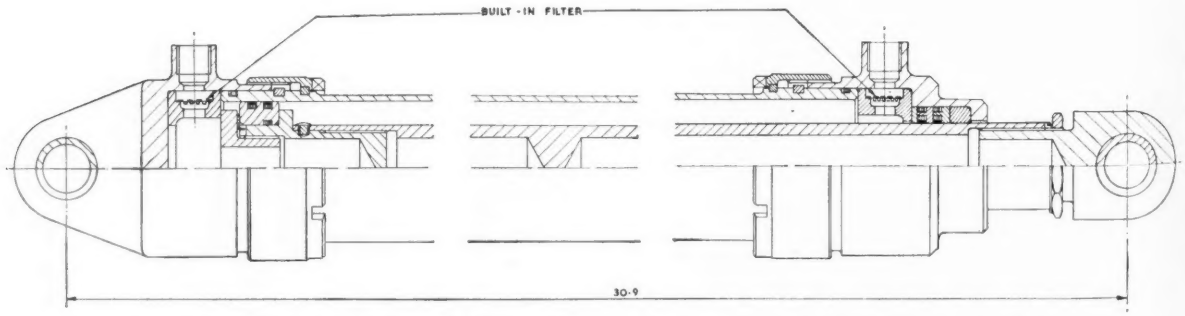


FIGURE 18. Standard 4,000 lb./sq. in. jack. Piston travels 24 in. Useful extending load 14,080 lb.

units were connected with the life of the dynamic seals and in view of the growing life expectancy, particularly in civil aircraft, this work is still proceeding at a high level of priority.

Strangely enough, extrusion of the rubber rings has not been as severe as was originally anticipated, but secondary effects, such as cylinder scoring and the turning of rubber rings, have been pronounced, mainly in jacks of large diameter.

The measures used to overcome these difficulties were to adopt a different seal design for cylinder bores in excess of 1½ in.: Fig. 19 shows the modified arrangement where the rubber rings are placed side by side and the soft rubber ring is backed by a hard packing which has a higher resistance to extrusion.

The rectangular section of these rings has increased the resistance to turning within the groove, and the scoring of the cylinders has been overcome by adequate proportioning of the piston lands and by the choice of piston bearing materials.

Venting of the piston land contained between the seals was found to increase the life of packings and furthermore, has allowed a more accurate prediction to be made of gland friction. To estimate frictional losses in jacks, some laboratory work was done to obtain the coefficient of friction between rubber and steel at different pressures.

Measurements were made of the force required to move a piston in hydraulic balance against the friction of two flexible packings at different speeds.

The results of these tests are shown in Fig. 20 which gives the variation of friction with pressure, and shows that some gain in efficiency can be expected by raising the pressure to 4,000 lb./in.²

5.5. HYDRAULIC MOTOR

The demand for an efficient high speed hydraulic motor is relatively new in aircraft hydraulic systems: it is now required for certain flap mechanisms and servo actuators.

In 1948 an experimental 10 h.p. motor was designed, of the type shown in Fig. 21. It consisted of a rotating cylinder block, attached to the output shaft, and of a swashplate fixed relative to the motor body. A ported distribution system was used, located at the rearmost face of the rotating cylinder block.

Although the performance of this motor was good at low pressures, at high pressures the deterioration of the cylinder block distribution face due to scoring was excessive. After several experiments with different grades of materials, and re-adjustments of sealing lands, the design had to be abandoned in favour of the one shown in Fig. 22.

In this case the cylinder block is fixed relative to the motor casing and the swashplate forms part of the rotating output shaft. Power is transmitted to the swashplate by five cylinders and plungers. The distribution of the fluid to each cylinder is done by means of cam-operated slide valves, each valve being located, together with its cylinder, in a compound barrel for ease of adjustment.

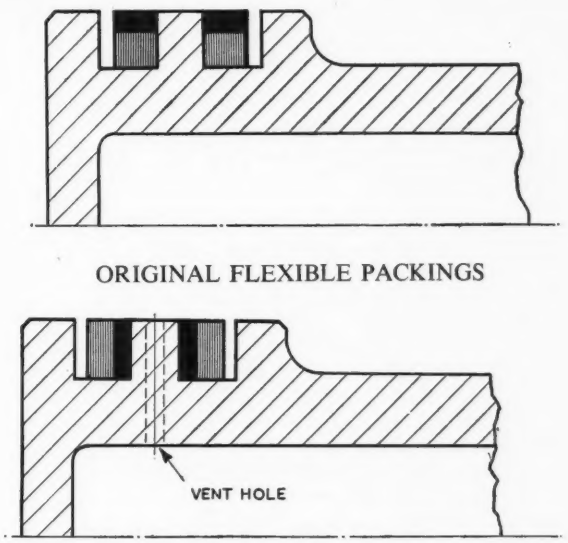


FIGURE 19. Modified flexible packings.

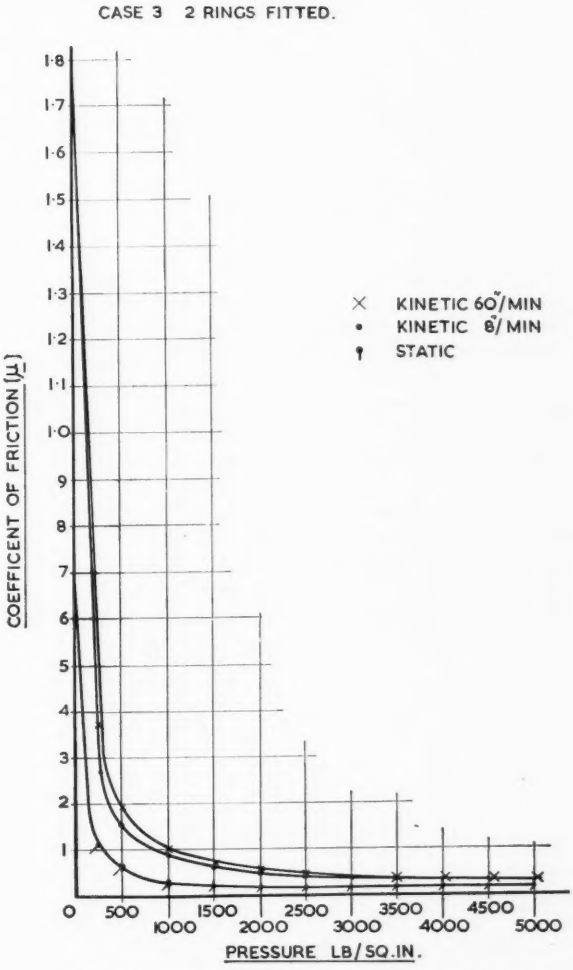


FIGURE 20. Variation of friction of flexible packings.

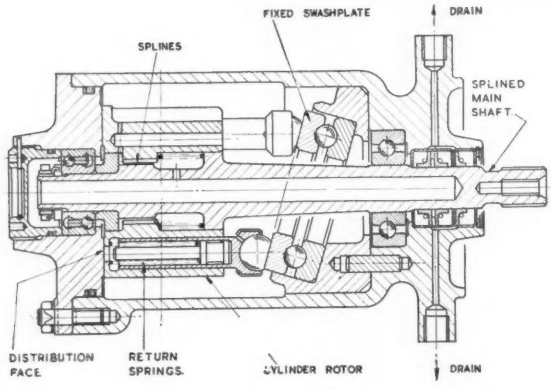


FIGURE 21. Rotary cylinder block hydraulic motor.

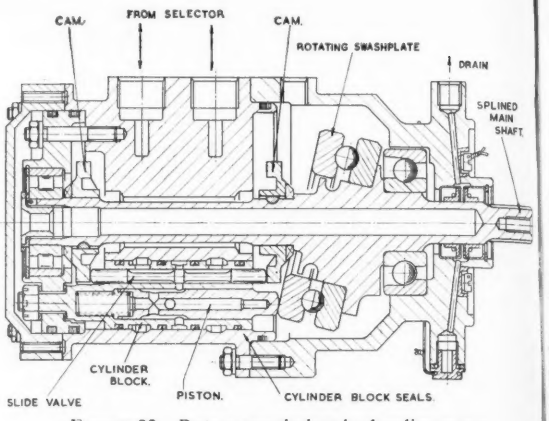


FIGURE 22. Rotary swashplate hydraulic motor.

Notwithstanding the more complicated nature of this motor, the only difficulty encountered was the rapid deterioration of the cylinder block packings, which were originally made of 90 Shore hardness rubber: this material was losing its hardness due to local high frequency impulses and was extruding into the system after a running period of the motor of approximately half an hour's duration.

This difficulty was completely overcome by substituting split plastic rings, within the existing grooves; one unit, after passing through the type approval test, has undergone several experiments running at 3,000 r.p.m. for several hours, without any deterioration, and other motors of this type are running on aircraft and on aircraft rigs with complete reliability.

6. Fire Hazard

An experiment made on the inflammability aspect of atomised D.T.D.585 fluid should be mentioned: a pipe was drilled to give an orifice diameter of approximately 0·0095 in. to simulate cracked pipe conditions, and pressure was supplied to this while the flame of a blow lamp was applied to the spray issuing from the orifice. This was repeated with different pressures ranging up to 5,000 lb./in.^{2}.

It was found that self ignition was not possible under conditions of normal temperature and pressure. When the jet velocity was high, the spray would blow itself out as soon as the ignition flame was removed. The spray would continue to burn after removal of the igniting flame only when the jet velocity was relatively low and corresponded to pressures between 200 lb./in.^{2} and 2,000 lb./in.^{2}. With very low jet velocities corresponding to pressures below 200 lb./in.^{2}, no atomisation occurred and therefore, there was no direct fire risk.

It was concluded that raising the pressure from 2,500 lb./in.^{2} to 4,000 lb./in.^{2} would, if anything, reduce the fire hazard.

7. Conclusion

There is little doubt that the 4,000 lb./in.^{2} aircraft hydraulic system is here to stay. It has by now passed out of the experimental stage and has flown on enough aircraft to convince both the users and the manufacturers that its reliability is as good as that of any other hydraulic system of equivalent power.

There is still plenty of scope in improvement, particularly on the efficiency and life of flexible packings, but this is a standing problem in all hydraulic applications and not only peculiar to the higher pressure: this kind of development is necessary to meet the ever-growing requirements of users for greater reliability; work is well under way and a successful future for the 4,000 lb./in.^{2} system can be forecast with confidence.

ACKNOWLEDGMENT

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The Arithmetic of Airworthiness

by

WALTER TYE, O.B.E., B.Sc., F.R.Ae.S.

(Chief Technical Officer, Air Registration Board)

Introduction

One of the many problems facing the aeronautical engineer is to make a vehicle, the reliability of which is tolerable, from an assembly of bits and pieces which, individually, are more or less unreliable. The practical answer has been to duplicate, triplicate, and generally to multiply the items about which doubt is felt.

This approach to reliability (and hence to safety) finds its way into codes of airworthiness, either as straightforward demands for duplication, or as requirements that no single failure should cause trouble.

On the whole these intuitive assessments of the probability of failure, and the design consequences in terms of duplication, seem to have been sound. It is, however, as well to examine the problems numerically, if we can. Possibly no very clear and decisive answers will emerge, but a little light may be shed on the paths we seek to follow.

The object of this present paper is a modest one. It merely serves to indicate some of the ways in which probability calculations are of value in airworthiness work, particularly with reference to problems associated with the search for safety by duplication, triplication (or worse).

1. A Simple Example of "Probability"

Probability calculations were first made in connection with games of chance. It is a convenient preliminary to the calculations which follow to consider the simple business of throwing poker dice, which have six sides, marked Ace, King, Queen and so on. There are six ways in which a die can fall so that the probability of any particular side (say, the Ace) falling uppermost is 1 in 6. We will call this probability p, and thus

$$p=\frac{1}{6}$$

Now, suppose we throw the die twice, there are six possible results of the first throw, and six completely independent possible results of the second throw. Hence, there are 36 possible results of the two throws and these combinations are illustrated in Fig. 1. But of all these 36 possible results, there is only one combination giving an Ace on both occasions. Hence the probability of two Aces is 1/36. Reference to Fig. 1 also shows that there are 25 ways in which neither die will show an Ace, and 10 ways in which one or the other die will show an Ace. Hence the probability of no Aces is 25/36 and of one Ace is 10/36. These results can be obtained, without the use of Fig. 1, in the following way:—

The probability of not throwing an Ace in one throw is

$$(1-p)=\frac{5}{6}.$$

So the probability of not throwing an Ace on either occasion is,

$$(1-p)^2=\frac{25}{36}.$$

The probability of not throwing an Ace on the first throw is 5/6 and of throwing an Ace on the second throw is 1/6, so the probability of this combination is

$$(1-p)\,p=\frac{5}{36}.$$

But the combination can occur in the opposite sequence (*i.e.* an Ace on the first throw, and other than an Ace on the second throw). Hence, the probability of one or other of two throws being an Ace is

$$2\,(1-p)\,p=\frac{10}{36}.$$

Finally, the probability of throwing an Ace on both occasions is

$$p^2=\frac{1}{36}.$$

A A	K K	Q Q	J J	10 10	9 9
A 9	K A	Q K	J Q	10 J	9 10
A 10	K 9	Q A	J K	10 Q	9 J
A J	K 10	Q 9	J A	10 K	9 Q
A Q	K J	Q 10	J 9	10 A	9 K
A K	K Q	Q J	J 10	10 9	9 A

FIGURE 1. All possible combinations of throwing a dice twice.

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It will be noted that if these probabilities be added, the sum is unity.

$$(1-p)^2+2(1-p)p+p^2=1$$

$$\frac{25}{36}+\frac{10}{36}+\frac{1}{36}=1.$$

This is as it should be, since a probability of one indicates certainty and it is certain that one of the several combinations will appear.

The foregoing example makes use of two important rules on which probability calculations are based. The first is that if p_1 is the probability of a certain event, and p_2 the probability of another independent event, then the probability of the two events occurring together is $p_1\ p_2$. The second is that if p_1 is the probability of a certain event and p_2 the probability of another event, and if the two events are mutually exclusive, the probability of one or the other event occurring is p_1+p_2.

2. A Slightly More Complicated Example

Consider next a rather more complicated example in which a series of four throws is made. The probability of not throwing an Ace at all is

$$(1-p)^4.$$

Calling the throws A, B, C and D respectively, the probability of A, B, C not being Aces and of D being an Ace is

$$(1-p)^3\,p.$$

But there are four possible combinations of this throw,

Not an Ace	*Ace*
$A\ B\ C$	D
$A\ B\ D$	C
$A\ C\ D$	B
$B\ C\ D$	A

So the probability of throwing one Ace is

$$4(1-p)^3\,p.$$

The probability of A and B not being Aces and of C and D being Aces is

$$(1-p)^2\,p^2.$$

But there are six possible combinations of this throw,

Not an Ace	*Ace*
$A\ B$	$C\ D$
$A\ C$	$B\ D$
$A\ D$	$B\ C$
$B\ C$	$A\ D$
$B\ D$	$A\ C$
$C\ D$	$A\ B$

So the probability of throwing two Aces is

$$6(1-p)^2\,p^2.$$

If we continue in this way, duly considering the possible combinations of each throw, the results are as follows:

No. of Aces	*Probability*	*Numerical Value of Probability*
No Aces	$(1-p)^4$	625/1,296
1 Ace	$4(1-p)^3\,p$	500/1,296
2 Aces	$6(1-p)^2\,p^2$	150/1,296
3 Aces	$4(1-p)\,p^3$	20/1,296
4 Aces	p^4	1/1,296

The terms in the middle column are recognisable as the binomial expansion of

$$[(1-p)+p]^4,$$

that is

$$[(1-p)+p]^4=(1-p)^4+4(1-p)^3\,p+6(1-p)^2\,p^2+4(1-p)\,p^3+p^4.$$

In its general form the binomial expansion is

$$[(1-p)+p]^n=(1-p)^n+n(1-p)^{n-1}p+\frac{n(n-1)}{2!}(1-p)^{n-2}p^2$$

$$\text{- - - - }\ n(1-p)\,p^{n-1}+p^n \quad . \quad . \quad (1)$$

Thus, if we make a series of n throws and we wish to know the probability of getting exactly r Aces, we take the $(r+1)^{\text{th}}$ term of the above expansion. For instance, if we make a series of six throws and hope to get two Aces (no less, no more), the probability of success is given by the third term, namely

$$\frac{n(n-1)}{2!}(1-p)^{n-2}p^2=\frac{6\times5}{1\times2}\left(\frac{5}{6}\right)^4\times\left(\frac{1}{6}\right)^2=0{\cdot}201.$$

In other words, the probability is about 1 in 5, or in betting language, the odds are 4 to 1 against success. However, as the object is not to assist in playing poker dice, we will next turn to aeronautical problems.

3. Some General Rules Applied to Aeronautical Problems

A class of aeronautical problem which is closely analogous to the dice example concerns probability of failure of items of equipment or engines. For example, we may be able to tell from records of failures that the probability of a particular item failing in a particular flight is p, and we may wish to estimate the probability of failure of one, two, or three of these items when there are say, four such items carried in the aeroplane.

Now if p is the probability of failure of a particular item during the flight, then the probability that the item will not fail is $1-p$. By analogy with the dice example, if there are n such items, the probability of F items failing is given by the $(F+1)^{\text{th}}$ term of the binomial expansion of $[(1-p)+p]^n$. Thus, if there are n items, the probability P of F failures occurring in a flight is

$$P=\frac{n!}{F!\,(n-F)!}(1-p)^{n-F}p^F \quad . \quad (2)$$

$$=C(1-p)^{n-F}p^F. \quad . \quad . \quad (3)$$

In these aeronautical problems the number (n) of similar items in an aeroplane is usually small, *e.g.* four engines, four generators, two altimeters, and so on. For convenience, therefore, we can write down once and for

TABLE I

	Coefficient C					
n items / *F failures*	1	2	3	4	5	6
0	1	1	1	1	1	1
1	1	2	3	4	5	6
2	—	1	3	6	10	15
3	—	—	1	4	10	20
4	—	—	—	1	5	15
5	—	—	—	—	1	6
6	—	—	—	—	—	1

all the coefficients C corresponding to the first few values of n and F. These are shown in Table I.

A typical figure for the probability p of failure of a particular item (engine or equipment) in one flight is one in 1,000. There is, of course, considerable variation, but for immediate purposes the figure of one in 1,000 is of the right order. Thus, when we write down the probability P of multiple failures it will be of the order

$$P = C\,(1-p)^{n-F}p^F$$
$$= C\,(0{\cdot}999)^{n-F}\,(0{\cdot}001)^F$$

and bearing in mind that n is usually a small number (*e.g.* two or four) to a very close approximation this can be written as

$$P = C\,p^F. \quad . \quad . \quad . \quad (4)$$

This, in conjunction with Table I, gives quick answers. For example, if the probability of one item failing in a flight is 1/1,200, and there are four such items, the probability of three out of the four items failing is

$$P = 4\left(\frac{1}{1{,}200}\right)^3$$

or one in 432 million flights.

4. Some Conclusions Regarding Duplication and Triplication

With Table I and equation (4) for reference purposes, certain practical conclusions immediately emerge. If we take, as a convenient typical figure, the probability of failure of an item as one in 1,000 flights the effects of duplication, triplication and so on are shown in Table II. In this, complete independence of the items is assumed.

Table II shows that if the criterion is the frequency of complete failure, duplication gives a thousandfold improvement and triplication a millionfold improvement. Thus with instruments, where safety is often assured if one of the instruments survives, duplication pays enormous dividends.

Table II also illustrates the point sometimes used as an argument against duplication, that the more items there are the more there are to go wrong. The second column shows that duplication doubles and triplication triples, the frequency of one item failing, and hence the amount of unserviceability is proportional to the degree of multiplication of items. While this doubling or trebling of unserviceability is not to be taken lightly, the enormous potential gain in safety may make it a small price to pay.

It is also of interest to consider the feasibility of dispensing with duplication by improvement of basic reliability. If, as a criterion, complete failure must not occur more often than once in a million flights, this can be achieved by

(*a*) a single item with a probability of failure of 1/1 million;
(*b*) duplicated items each with a probability of failure of 1/1 thousand;
(*c*) triplicated items each with a probability of failure of 1/1 hundred.

An item with an exceptionally bad rate of failure (class (*c*) $p = 1/100$) might fairly readily have its reliability raised tenfold to bring it into class (*b*) ($p = 1/1{,}000$). Hence the necessity to triplicate would be avoided by improvement in basic reliability. However, it would be much more difficult to raise reliability to class (*a*), as this would mean making an item which, in practical terms, never failed. The task would amount to improving an item of moderate reliability to virtual infallibility, and avoiding in the process more than doubling its weight. This might often prove impossible, forcing the acceptance of duplication as the only practical solution.

The foregoing paragraphs apply particularly to the case where, provided that a single item survives, safety is assured (*e.g.* in the case of duplicated air speed indicators). Where we are concerned with the supply of power of one sort or another and where, in emergencies, it is important that a certain minimum power supply be maintained, different conclusions may well arise, as is illustrated next.

5. An Example of the Choice of Number of Items

As an example of the use to which this kind of arithmetic can be put, suppose we wish to decide whether to use two, three or four generators. The requirement might be that for

(*a*) every day purposes an output X was necessary;
(*b*) on one occasion in 1,000 an output $X/2$ would be accepted;
(*c*) on one occasion in 1,000,000 complete failure would be accepted.

Suppose further that we cannot expect the probability of failure of the generator-engine combination to be lower than one in 500 flights. Table III puts down in tabular form the probability of failure of various numbers of generators.

To comply with the complete failure requirement (*c*), two generators are insufficient, but three or four would suffice. If three generators are provided the "half-power" requirement (*b*) must be met with two

TABLE II

No. of items	*Probability of* One failing	All failing
Single	$1/10^3$	$1/10^3$
Duplicated	$2/10^3$	$1/10^6$
Triplicated	$3/10^3$	$1/10^9$
Quadruplicated	$4/10^3$	$1/10^{12}$

generators failed (as the one failed case occurs too often). Also, if four generators are provided, the half-power requirement must be met with two failed.

Hence the design rests between

Three generators each with a power $X/2$,
Four generators each with a power $X/4$.

Provided that generator weight was roughly proportional to power, quadruplication seems more efficient than triplication.

A very different answer would emerge if the basic reliability were raised. Suppose that the probability of failure were reduced to 1/2,000 (a fourfold improvement), then with two generators complete-failure probability is

$$\left(\frac{1}{2{,}000}\right)^2 = \frac{0{\cdot}25}{10^6} \text{ which meets condition } (c),$$

and one-failure probability is

$$2\left(\frac{1}{2{,}000}\right) = \frac{1}{10^3} \text{ which just meets condition } (b).$$

Hence, by a feasible improvement in reliability, instead of quadruplication, duplication becomes a possibility. Although this might not mean any direct weight saving, it gives an eightfold saving in the frequency of unserviceability.

6. Independence

Before leaving these examples of duplication, triplication and so on, a word must be said about independence of the items. In the previous examples complete independence has been assumed. In practice, great care has to be taken to achieve this.

A measure of interconnection may exist between the items or systems in a variety of ways, such as:—

(*a*) there may be a physical connection, there being a part which is common to both systems;
(*b*) the failure of one item may impose a greater strain on the other item, increasing its probability of failure;
(*c*) there may be external conditions likely to affect both items.

A fuel collector box which serves two adjacent engines is an example of (*a*). An under-powered twin-engined aeroplane in which the failure of one engine imposes a burden on the second engine, illustrates (*b*). Duplicated A.S.I. systems, both of which fail if the pitot heads ice up, is an example of (*c*).

The important—indeed the vital—point is that possibility of failure of common parts must be virtually eliminated if credit is to be taken for independence. Consider an example of two engines, the probability of failure of either one being one in 1,000 flights. Thus, if the installation is completely independent, the probability of double failure is one in 1,000,000 flights. Suppose however that a common part is introduced which stops both engines if it fails. If we impose a limit that this common part must not increase the double-failure rate by more than 10 per cent., then the acceptable probability of failure of the common part must not exceed one in 10,000,000 flights. In practical terms this means that common parts have to be as reliable as primary structure, and that the lower degree of reliability associated with most mechanisms or electrical parts is not satisfactory.

TABLE III

	Probability			
No. provided \ *No. failed*	1	2	3	4
2	$4/10^3$	$4/10^6$	—	—
3	$6/10^3$	$12/10^6$	$8/10^9$	—
4	$8/10^3$	$24/10^6$	$32/10^9$	$16/10^{12}$

7. Cumulative Probability of Failure of Larger Numbers of Items

Another class of problem concerns equipment which contains a number of individual components, the failure of any one component being sufficient to cause failure of the whole assembly. For example, radio sets with a large number of valves may come in this category. We are concerned in this case with the probability of *one or more* items failing. Reverting to the original expression, the probability of no failures at all was

$$(1-p)^n$$

where

p was the probability of an individual item failing,
n was the number of items.

Thus, the probability that one or more items will fail is

$$P = 1-(1-p)^n \quad . \quad . \quad . \quad (5)$$

In practical cases p may again be of the order 0·001 and n may be, say, 20. If the above expression is expanded it becomes

$$1-\left[1-np+\frac{n(n-1)}{2}p^2 - - - -\right]$$

$$= np\left[1-\left(\frac{n-1}{2}\right)p - - - -\right]$$

The second (and subsequent) terms will usually be negligible, provided—as is usual—that np is small compared with unity. Hence to a close approximation the risk of failure of an apparatus with n similar items is given by

$$P = np \quad . \quad . \quad . \quad (6)$$

If a case should occur in practice where the value of np is large then this approximation no longer holds good. The expansion of equation (5) can be written

$$P = 1-\left[1-np+\frac{(np)^2}{2!}\left(1-\frac{1}{n}\right) - \right.$$

$$\left. - \frac{(np)^3}{3!}\left(1-\frac{1}{n}\right)\left(1-\frac{2}{n}\right) - - - -\right]$$

If n is a large number, terms such as $1/n$, $2/n$, are negligibly small, so this becomes

$$P = 1-\left[1-np+\frac{(np)^2}{2!}-\frac{(np)^3}{3!} - - -\right]$$

and this will be recognised as

$$P = 1-e^{-np}. \quad . \quad . \quad . \quad (7)$$

This is shown plotted in Fig. 2.

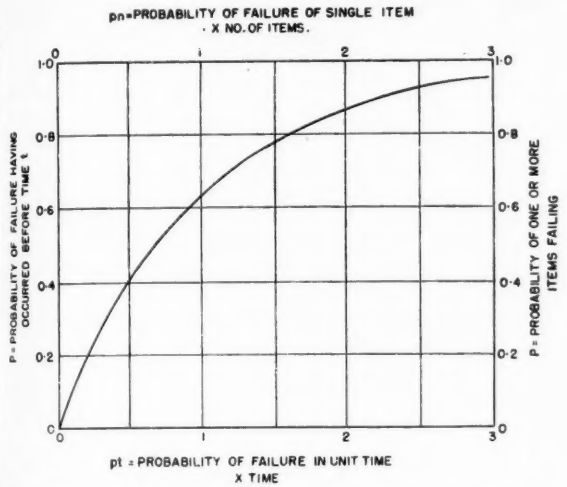
pn=PROBABILITY OF FAILURE OF SINGLE ITEM
X NO. OF ITEMS.
P = PROBABILITY OF FAILURE HAVING OCCURRED BEFORE TIME t
P = PROBABILITY OF ONE OR MORE ITEMS FAILING
pt = PROBABILITY OF FAILURE IN UNIT TIME
X TIME

FIGURE 2. Probability $P=1-e^{-\rho t}$ and $P=1-e^{-np}$.

8. The Effect of Time of Flight

In previous sections it has been assumed that the probability of failure of one item is constant regardless of the duration of the flight. For items which run throughout a flight, *e.g.* engines, it would be more likely that, increasing time of flight would increase the probability of failure during a flight. There is some evidence that with engines, the probability of failure is directly proportional to time of flight. Thus we may write

$$P=\rho t. \quad . \quad . \quad . \quad (8)$$

(*See* the Appendix for further discussion of this assumption.)

A point of interest arises here in regard to multiple failures in a particular flight. We have already seen that the probability of F failures is approximately

$$P=C\,p^F$$

where C depends on the number of items n and failures F. If we now write $p=\rho t$

$$P=C\,\rho^F\,t^F. \quad . \quad . \quad . \quad (9)$$

Thus for double failures (*e.g.* two power units)

$$P=C\,\rho^2\,t^2.$$

Hence, if the duration is doubled, the risk of double failure increases fourfold. It is also noteworthy that if the basic reliability of the item is halved, giving twice the value of ρ, the risk of double failure also increases fourfold. These effects are of practical importance in connection with the suitability of equipment and power plant for long range use. For example, if a particular power plant has a rate of failure of one in 2,500 hours, in a twin-engined short range ($2\frac{1}{2}$ hour duration) aircraft, the probability of failure of both engines is

$$\left(\frac{2{\cdot}5}{2{,}500}\right)^2=\frac{1}{10^6}$$

or one in 1,000,000 flights; whereas in a long range (10 hours duration) four-engined aircraft, the probability of two engines failing is

$$6\left(\frac{10}{2{,}500}\right)^2=\frac{96}{10^6}$$

or about one in 10,000 flights. The former case might be an acceptable risk, while the latter case in which the risk is 100 times greater might only be acceptable if the aircraft had adequate two-engine inoperative performance.

9. Connection Between Probability of Failure and Rate of Failure

In the dice example, the probability of a certain result occurring in any one throw is exactly 1/6. We can reach this conclusion by examining the nature of the particular problem and we do not need to test it by throwing dice to be certain of the truth of our conclusion. If we felt sufficiently industrious we could arrive at the same conclusion by the experimental method of throwing a dice a very large number of times and, in the long run, a particular side would fall uppermost on 1/6 of all the throws. If, however, we got tired after a dozen or so throws, then there is little likelihood that a particular face would have turned up on exactly 1/6 of the occasions. Hence, a brief experiment would be likely to lead to a false conclusion. This is of practical importance since, in aeronautical problems, there is not usually an *a priori* argument by which we can arrive at the probability, and we are therefore obliged to assess it from observations of the rate of failure.

In the previous sections it has been assumed that the failure of a part of an aeroplane (whether it be an engine or an item of equipment) is as likely to fail at one moment as at any other moment. This is a convenient assumption, but care must be taken to check its validity. For example, if fatigue or wear is the cause of failure, then the part is less likely to fail when it is new than when it is old. There is some evidence that for many items of equipment and instruments, length of previous service has no bearing on the probability of failure. However, before using any set of failure data it is as well to examine it for trends and not automatically to assume that probability of failure is constant.

Reverting to the number of observations necessary to establish probability with reasonable accuracy, a simple example will illustrate the problem. Suppose that the probability of a certain event (*e.g.* failure) occurring in a trial is 0·1, and suppose that 100 trials are made. If in this limited number of trials the particular event occurred 10 times—giving a mean rate of $10/100=0{\cdot}1$, the test result would give the exactly correct value of probability.

But it is possible in such a limited test that the particular event may occur any number of times between zero and 100. By working out the individual terms of the binomial expansion of $(0{\cdot}9-0{\cdot}1)^{100}$ as described in previous sections the probability of any specific number of occurrences of the event can be calculated, with the following results:—

Number of occurrences	0 to 4	5	6	7	8	9	10
Probability of occurrences	Very small	0·03	0·06	0·09	0·12	0·13	0·135
Number of occurrences	11	12	13	14	15	16 to 100	
Probability of occurrences	0·12	0·11	0·08	0·05	0·03	Very small	

If we had no prior knowledge that $p=0{\cdot}1$ and were relying solely on this test to provide the answer, it will be seen that the probability of being just right (*i.e.* observing 10 occurrences) is very small, in fact only 0·135.

In practice we are concerned with making an assessment within certain limits. For instance, if ± 20 per cent. accuracy were acceptable, in this example we should be content if 8, 9, 10, 11 or 12 occurrences of the event were observed. The probability of one or other of these five answers being obtained is the sum of the individual probabilities and equals about 0·6. Similarly there is a probability of about 0·9 that the observation will be within ± 40 per cent. of the true value.

Applying this example to the typical problem of observing the frequency of occurrence of failures, it is evident that if we have a sample of only 10 failures any conclusions we draw regarding the probability of failure are liable to considerable inaccuracy. In practice, samples of about 100 failures are the smallest one can accept in order to make assessments of probability of failure with reasonable confidence of accuracy.

10. Conclusions

The solution of engineering problems of duplication, triplication and so on can be assisted by simple probability calculations. The probability of failure of any one item (in a set of similar items each independent of the others) is proportional to the number of items. The probability of failure of all the items in the set is the product of the individual probabilities. Hence duplication or triplication (provided the items are truly independent) results in great reduction in the risk of complete breakdown. Consideration of the general level of reliability of most present day "moving parts" (mechanisms, instruments, engines and so on) suggests that it may often be more practical to achieve the necessary overall level of safety by duplication rather than by increase of basic reliability of the item. In other cases modest increase of reliability permits reduction of numbers of items. Each case therefore warrants examination if the most efficient answer is to be found.

When multiplication of items or systems is used to improve safety, it is extremely important that failures which would affect more than one item should be eliminated. For example, the integrity of common parts should be above suspicion. When deducing probability of failures from observations of rates of failure, it is unwise to rely on small numbers of observations.

APPENDIX

THE EFFECT OF TIME

It was stated in the text that for some components the probability of failure is likely to be directly proportional to time of flight. Equation (8) was thus written as

$$P=\rho t. \qquad . \quad . \quad . \quad (8)$$

The implication of this is that if t were very large, so that $\rho t=1$, the probability of failure having occurred would be one, and failure of the item would be a certainty by a finite time $t=1/\rho$. In practice the time of flight and value of ρ are such that ρt is very small. Hence practical evidence supporting equation (8) cannot properly be extrapolated to values such as $\rho t=1$.

In another connection, however, high values of ρt are of importance. In establishing overhaul lives, we are concerned with the way in which probability of failure is affected by time measured from the previous overhaul. For some items (those in which fatigue and wear have no important bearing on failure) there are indications that the probability of failure in unit time is independent of the time which has elapsed since previous overhaul. In such cases we can write probability of failure in time δt, as $\rho\delta t$, where ρ is constant.

The probability of no failures having occurred after x intervals of time δt

$$=(1-\rho\delta t)^x.$$

Writing $t=x\delta t$, this becomes

$$\left(1-\rho\frac{t}{x}\right)^x=1-\rho t+\frac{(x-1)}{x}\frac{\rho^2 t^2}{2}\ldots\ldots$$

If δt is very small, x is large, and this series becomes

$$1-\rho t+\frac{\rho^2 t^2}{2}\ldots\ldots=e^{-\rho t}.$$

Thus the probability of failure occurring before time t is reached is

$$P=1-e^{-\rho t}. \qquad . \quad . \quad . \quad (10)$$

Equation (10) is shown plotted in Fig. 2. It will be noted that when $t=0$ the probability of failure having occurred is zero, and that the probability of failure having occurred does not reach one (*i.e.* does not approach certainty) until time becomes infinite. For small values of ρt, equation (10) can be written, to a close approximation, as

$$P\doteqdot\rho t.$$

Thus it will be seen that for time of flight problems it is immaterial whether equation (8) is an exact statement, or whether it is simply a close approximation of equation (10). When, however, one is concerned with problems in which ρt is of the order of unity, it is necessary to distinguish clearly between the significance of the two equations. Equation (8) does not represent constant probability of failure in unit time, but in fact is consistent with a probability of failure which increases as time proceeds.

It is noteworthy that the two equations

$$P=1-e^{-\rho t} \qquad . \quad . \quad . \quad (10)$$

$$P=1-e^{-np} \qquad . \quad . \quad . \quad (7)$$

are of the same form.

Equation (7) is the probability of at least one item failing out of a set of n similar items, where p is the probability of any one item failing. Equally, if there is one item and it is exposed to n events with p the probability of a certain result (*e.g.* failure) then the probability of this result having occurred before the n^{th} event will be given by equation (7). This is clearly directly analogous to the case of running continuously with a constant probability of failure in any element of time. Hence the correspondence of ρt and np is readily seen.

TECHNICAL NOTES

Contributions to this Section of the JOURNAL *are eligible for Journal Premium Awards; they should be as brief as possible and will normally be published within two months of being received.*

Note on the Comparison of a "Wake Brake" and a Parachute for the Landing of Aeroplanes

by

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THE AVAILABLE METHODS of braking a modern aeroplane with its high landing speed are not entirely satisfactory[1]. This difficulty in braking is particularly noticeable with pure jet aircraft. Owing to the absence of propellers, reversible pitch propellers are no longer a solution to this problem and the undercarriage can be simplified so that it occupies a smaller fraction of the all-up weight of the aeroplane.

On landing, the brakes inside the wheels of the aeroplane are applied. However, the smaller wheels, now universally adopted for the pure jet aeroplane, cannot incorporate sufficient frictional area to supply the braking required and a long landing run may be necessary. It has been reported[2] recently that in the United States "cerametal" brake linings are to be used in an attempt to increase the braking force available for landing and in future, disc brakes will certainly be used for aeroplane wheels. Nevertheless, there are limitations to the amount of braking which can be absorbed by the tyres, due to heat build-up in the rubber, and after the application of the brakes, a short period elapses before the brakes become fully effective[1]. When rain or ice are on the aerodrome, the braking of a pure jet aeroplane is even more difficult due to the lower friction of the rubber tyres. All these problems are associated similarly with the landing of an aeroplane on an aircraft carrier deck where an arrester wire or even a corrugated rubber deck are employed, although recently the adoption of the angled deck, at a line 8° with the fore-and-aft line, has received prominence.

The release of a parachute behind an aeroplane is a common procedure for braking on landing, although it is realised that this method is not an ideal solution for two reasons. Firstly, tail buffeting is caused by the use of a parachute downstream of the tail[3] and secondly, a parachute can only be used once before repacking. Unless a spare parachute is carried, disaster may result from a misjudged landing approach.

Brown[3] states that the usual size of a parachute used for braking an aeroplane is 7 ft. and it is the purpose of this note to compare simply the drag of such a parachute with the drag of a new device called a "Wake brake[4]." This new method of braking makes use of the large unstable flow produced by a free stagnation point (line) behind a wing using boundary layer suction at slots when the free stagnation point is not stabilised by a flap.

The layout of an aeroplane with a "Wake brake" is assumed in the note, although the scheme suggested is not necessarily the best attainable. Rear suction slots are placed at or near the roots of the wing and air is sucked through the slots by a bleed to the compressor of a gas turbine unit inside the aeroplane. The scheme is considered for a wing of 25 per cent. thickness, using results obtained from a two-dimensional section of the same thickness[4]*. An attempt is made to predict the performance of a similar scheme using a thinner and more practical wing. The braking effect of a 7 ft. diameter parachute is evaluated and compared with that of the "Wake brake." Further tests are recommended to determine whether a "Wake brake" scheme is in fact a practical proposition.

Notation

U_0	free stream velocity or landing speed
ρ	density of air
b	length of one suction slot along half span
c	mean chord of wing over length of span b
t	mean value of maximum thickness of wing over length of span b
ω	width of throat of rear suction slot
U_s	mean suction velocity at throat of rear suction slot
M	mass flow of air into gas turbine unit
C_Q	suction quantity coefficient per unit span of aerofoil
C_{D_W}	wake drag coefficient produced by "Wake brake"
D_W	drag corresponding to C_{D_W}
d	diameter of parachute
C_{D_p}	drag coefficient of parachute
D_p	drag corresponding to C_{D_p}

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*Certain assumptions are made in the simple calculations and these are pointed out.

1. BRAKING EFFECTS

1.1. *Use of a "Wake Brake"*

When the layout of an aeroplane with a "Wake brake" is assumed, the values selected for the dimensions of the aeroplane affect the performance predicted for the brake. However, the values chosen in this note will be such that the use of a "Wake brake" is not unduly favoured.

The first selection must be the gas turbine unit for the pure jet aeroplane envisaged, since it is known from wind tunnel experiments[4] that the suction quantity for this form of brake is large. The data available for this note gives the mass flow at sea level for one of the jet engines in common use as 110 lb./sec. and this figure will be used for these calculations.

With one turbine in the aeroplane, a wing span of 35 ft. will be considered. The thickness/chord ratio at the root of the wing will be in the range 12-22 per cent.[5]. However, no experimental figures are available for the unstable flow produced by a free stagnation point behind a wing within this thickness range, so the average thickness of the wing to which the suction slot is fitted, will be assumed firstly to be 25 per cent., the thickness of the wing used in the earlier experiments[4]. It will be further assumed that the mean chord of the wing over the length of the slots is 10 ft. Fig. 1 shows the suggested layout of the aeroplane and brake.

The theoretical values of some of the parameters of a 25 per cent. thick rear suction slot aerofoil are as follows. The velocity at the throat of the rear slot is $U_s = 1{\cdot}345 \times$ the free stream velocity U_0. Suction quantity coefficient $C_Q = 0{\cdot}0337$ and width of the throat of the slot $\omega = \text{chord}/40$. However, it was found in practice that $U_s = 2{\cdot}0\,U_0$ for removal of all the boundary layer into the rear slot. This is the value of the suction velocity to be used here.

With allowance for wind tunnel interference in the case of the experimental results on a 25 per cent. thick aerofoil, a reasonable value for the drag coefficient corresponding to the unstable flow is 0·4. This value applies at zero angle of attack and $U_s/U_0 = 2{\cdot}0$ and the value of C_{D_W} is increased with increase of either of these parameters.

Two rear suction slots are assumed for the aeroplane, as shown in Fig. 1, and the length of a slot b is to be determined.

Case (a) One Gas Turbine in the Aeroplane

Mass flow into slot

$$M = U_s \times 2b \times \omega \times \rho. \quad . \quad . \quad (1)$$

Now $U_s \geqslant 2U_0$ and $\omega = c/40 = \frac{1}{4}$ ft. At standard atmospheric conditions which are applicable for landing, $\rho = 0{\cdot}0768$ lb./ft.^{3}.

It will be seen from (1) that the required length of slot is inversely proportional to U_s, and therefore to U_0. The length of the slot b is plotted against U_0 from 80 to 200 m.p.h. in Fig. 2. At a landing speed of 120 m.p.h. (176 ft./sec.), the length of the slot is $b = 8{\cdot}15$ ft. for one assumed turbine of $M = 110$ lb./sec. sucking its air completely through the slot at $U_s/U_0 = 2{\cdot}0$. This length could be accommodated in a wing of 35 ft. span.

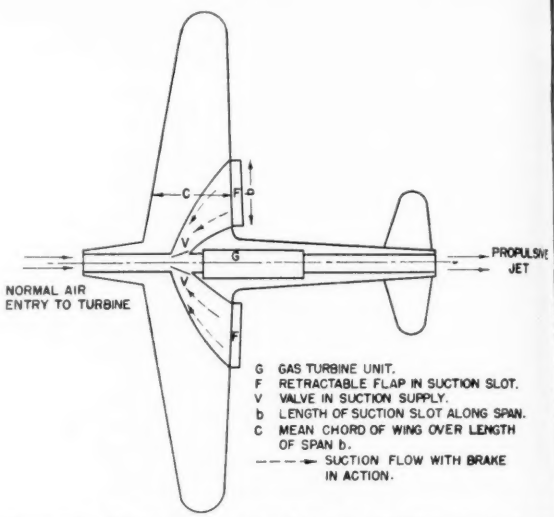

FIGURE 1. Diagram of suggested layout of "Wake brake" with pure jet aeroplane.

The value of b selected for any aeroplane should be the minimum value (corresponding to the maximum landing speed) since for lower landing speeds either U_s can be greater than $2U_0$ or a bleed of air taken through the rear slots so that $U_s/U_0 = 2{\cdot}0$.

Then the braking force of this scheme is

$$D_W = C_{D_W} \times \tfrac{1}{2}\rho U_0^2 \times 2bc \quad . \quad . \quad (2)$$

where $2bc$ is the plan area considered.

Therefore $$\frac{D_W}{\frac{1}{2}\rho U_0^2} = 0{\cdot}4 \times 2 \times 8{\cdot}15 \times 10$$
$$= 65{\cdot}2 \text{ ft.}^2 \text{ at } U_0 = 120 \text{ m.p.h.}$$

Alternatively, $D_W = 2{,}390$ lb. at $U_0 = 120$ m.p.h.

Also $$\frac{D_W}{\frac{1}{2}\rho U_0^2} = 0{\cdot}4 \times 2bc = 0{\cdot}4\,\frac{(40M)}{2U_0\rho}$$

from (1),

$$\omega = c/40 \text{ and } U_s = 2U_0$$

so that $$\frac{D_W}{\frac{1}{2}\rho U_0^2} = \frac{11{,}500}{U_0} \text{ ft.}^2$$

for one jet engine and $U_s/U_0 = 2{\cdot}0$. This relation is plotted in Fig. 2. Hence, the drag force of a "Wake brake" D_W increases linearly with landing speed if b is regarded as a variable. For a given aircraft and slot, D_W is proportional to the square of the landing speed.

Case (b) Two Gas Turbines in the Aeroplane

If it is assumed that two jet engines, each of mass flow 110 lb./sec., are fitted in the aeroplane then the length of the slot to be fitted in the wing is double the length for one turbine at the same landing speed. Hence, for the two engines breathing entirely through the rear slots, the drag corresponding to the unstable flow will also be double, or

$$\frac{D_W}{\frac{1}{2}\rho U_0^2} = \frac{23{,}000}{U_0} \text{ ft.}^2 \text{ for } U_s/U_0 = 2{\cdot}0.$$

However, it is unlikely that the span of the wing will be much greater and the doubled values of the length of the slot may be impossible to install.

Case (c) A Thinner Wing Section

In theory, the suction quantity required for thinner sections decreases as the square of the thickness/chord ratio, although in practice it was found that the suction flow for a 25 per cent. section was greater than the theoretical amount[4]. Some theoretical values are available for a 13¼ per cent. section with a rear suction slot. $C_Q = 0{\cdot}009$, slot velocity $= 1{\cdot}17U_0$ and width of slot $\omega = 0{\cdot}0074c$.

It will be assumed, although without any experimental evidence, that the wake drag coefficient is proportional to the thickness/chord ratio and that the actual slot velocity of a thinner wing is the theoretical slot velocity at the required thickness multiplied by the ratio of the actual to theoretical slot velocity of a 25 per cent. thick wing.

Therefore wake drag coefficient

$$\text{for } 13\tfrac{1}{4} \text{ per cent. wing} = 0{\cdot}4 \times 13\tfrac{1}{4}/25 = 0{\cdot}213,$$

and slot velocity at throat for

$$\text{for } 13\tfrac{1}{4} \text{ per cent wing} = \frac{2{\cdot}0}{1{\cdot}345} \times 1{\cdot}17U_0 = 1{\cdot}735U_0.$$

As before, mass flow $M = U_s \times 2b\omega \times \rho$.

For complete air intake through the slots for one turbine

$$M = 110 = 1{\cdot}735U_0 \times 2b \times 0{\cdot}074 \times 0{\cdot}0768$$

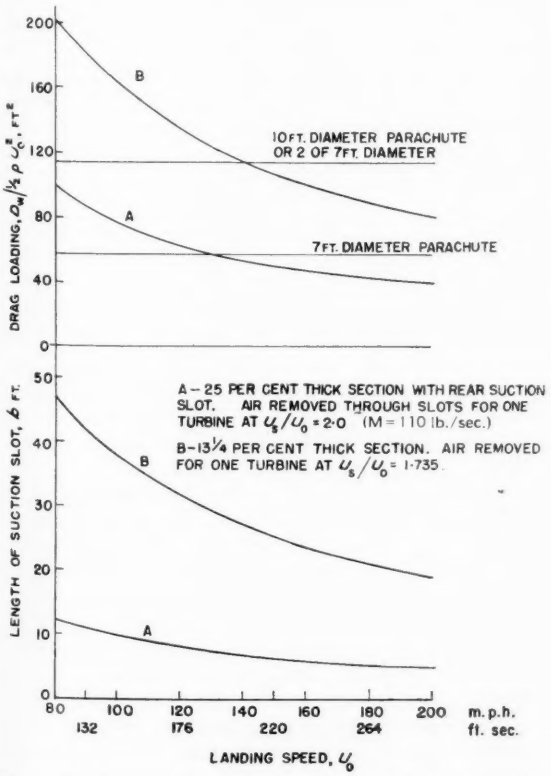
DRAG LOADING, $D_W/\frac{1}{2}\rho C_{D_W}$, FT.²
LENGTH OF SUCTION SLOT, b FT.
B
10 FT. DIAMETER PARACHUTE OR 2 OF 7 FT. DIAMETER
A
7 FT. DIAMETER PARACHUTE
A – 25 PER CENT THICK SECTION WITH REAR SUCTION SLOT. AIR REMOVED THROUGH SLOTS FOR ONE TURBINE AT $U_s/U_0 = 2{\cdot}0$ (M = 110 lb./sec.)
B – 13¼ PER CENT THICK SECTION. AIR REMOVED FOR ONE TURBINE AT $U_s/U_0 = 1{\cdot}735$
m.p.h.
ft. sec.
LANDING SPEED, U_0

FIGURE 2. Comparison of braking effects of "Wake brake" scheme and parachute.

where $c = 10$ ft. as before.

Therefore $U_0 b = 5{,}580$ ft.²/sec.

b is plotted against U_0 in Fig. 2.

If $U_0 = 120$ m.p.h. as before, then $b = 31{\cdot}8$ ft. This is a very long slot and could not be fitted in the design. The solution may be to use a shorter slot than predicted above and to withdraw only a bleed through the rear slots. Nevertheless a sufficient drag force must be available with the scheme.

$$\text{At 120 m.p.h. } \frac{D_W}{\frac{1}{2}\rho U_0^2} = C_{D_W} \times 2bc = 0{\cdot}213 \times 63{\cdot}6 \times 10 \text{ ft.}^2 = 135{\cdot}5 \text{ ft.}^2$$

for one assumed engine withdrawing all its air through the slots at $U_s/U_0 = 1{\cdot}735$. The relation between this drag loading and the landing speed is plotted also in Fig. 2.

If the assumptions for a thinner wing are correct, a very large drag force is available and it would be enough to remove only half of the air for the gas turbine through shorter slots. This would produce the same drag as a 25 per cent. thick wing with all the air removed through the slots.

1.2. *Release of a Parachute*

Brown[3] states that the diameter of a parachute released from the tail of an aeroplane for braking on landing is, in many cases, about 7 ft. This value will be used for comparison with the "Wake brake," although a larger size or two 7 ft. diameter parachutes are considered also.

There is some discrepancy in the published values for the drag coefficient of a parachute. Brown[3] gives the value of C_{D_p} as 1·07. A rather older source of information[6] gives 1·44 at 60 ft./sec. and Marks[7] tabulates C_{D_p} as 1·35. The drag coefficient of the 16 ft. diameter brake parachute of 24 per cent. porosity fitted as standard equipment on the U.S.A.F. F-94C Starfire is 0·49[8]. In order not to favour the "Wake brake" scheme, a value of C_{D_p} of 1·50 will be assumed in the following calculations.

Then the drag force of a parachute is

$$D_p = \tfrac{1}{2}\rho U_0^2 \times C_{D_p} \times \frac{\pi d^2}{4}$$

where d = diameter of parachute

or $D_p/\frac{1}{2}(\rho U_0^2) = 1{\cdot}175d^2$ ft.².

If $d = 7$ ft., $D_p/(\frac{1}{2}\rho U_0^2) = 57{\cdot}6$ ft.².

For $d = 10$ ft. (or a cluster of two parachutes of 7 ft. diameter), $D_p/\frac{1}{2}\rho_0^2 = 115$ ft.². The drag force of a parachute D_p is proportional to the square of the landing speed.

1.3. *Comparison of Braking Effects*

At a landing speed of 120 m.p.h. the wake drag of the suggested form of brake is $65{\cdot}2/57{\cdot}6 = 1{\cdot}135 \times$ that of a 7 ft. diameter parachute. In fact, the drag of a "Wake brake" scheme fitted in a 25 per cent. thick

Direction of air stream →

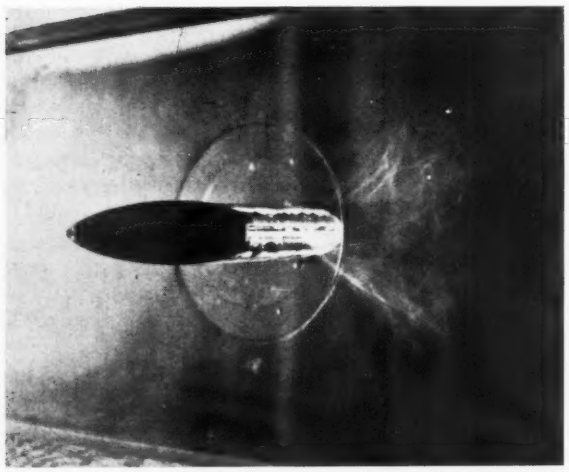

FIGURE 3. Unstable flow produced by a free rear stagnation point. Zero incidence, flap fully retracted and $U_s/U_0 = 2{\cdot}41$. Exposure of 1 sec.

wing, with all the turbine air removed through the rear slots at $U_s/U_0 = 2{\cdot}0$ is greater than that of a parachute up to a speed of $11{,}500/57{\cdot}6 = 200$ ft./sec. or 136·5 m.p.h. Above this speed the drag of a 7 ft. diameter parachute is greater than that of a "Wake brake" in a 25 per cent. thick wing with one gas turbine unit. If the whole of the air for two jet engines is removed through the rear slots of a 25 per cent. thick wing, the "Wake brake" produces a drag greater than that of a 7 ft. diameter parachute up to a speed of 273 m.p.h.

Although the calculations on the thinner wing with a rear suction slot are based on even more assumptions than those for the 25 per cent. thick wing, the results tend to indicate that a large drag is attainable with a thin wing and that a sufficiently large drag can be achieved by removing only part of the air for the turbine through slots of reduced length.

2. DISCUSSION OF PRACTICAL POINTS OF A "WAKE BRAKE" SCHEME

It has been reported[4] how the unstable flow about an aerofoil with a rear suction slot can be stabilised completely by a flap positioned to support the rear stagnation point and how in fact, the flow over the aerofoil is then extremely steady and of laminar form. It may appear therefore, that it would be advantageous to employ the suction slot as a control of the flow over the part of the wing covered by the slots when the aircraft is flying normally and the brake is not required. However, two difficulties are present. Firstly, the turbine performance is seriously reduced in flight when the ram effect is lost, as it would be in this case. Secondly, at normal aeroplane speeds, the mass flow to be removed through the slot is proportional to the aeroplane speed. Thus, the suction quantity would be prohibitive unless a very thin wing was adopted and the bleed from the rear slots increased as the aeroplane speed increased. With this in mind, the use of the rear suction slots must apparently be restricted to braking only.

Direction of air stream →

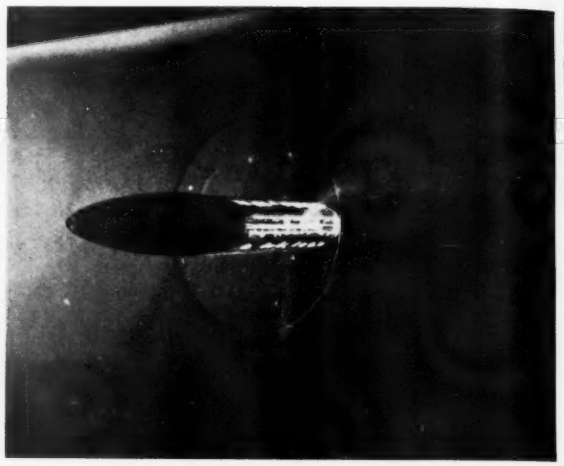

FIGURE 4. Unstable flow produced by a free rear stagnation point. Zero incidence, length of flap from rear of aerofoil/chord = 0·025 and $U_s/U_0 = 2{\cdot}05$. Exposure of 6 sec.

Consequently, the best way to adapt the device for use on landing and yet to provide no extra drag when in flight must be considered. One convenient solution appears to be a collapsible fairing in contact with the rear of the wing and closing the slot when the brake is not required. For landing, the fairing, which would be small for a thin wing, should be capable of being rapidly collapsed and withdrawn into the rear suction slot. At the same time, the valve to the forward air entry would be closed and the valve for the rear slots opened. In normal flight, the forward air intake would be used for suction to the gas turbine. With thinner wings operating on a bleed from the turbine, the front valve would not be fully closed when the brake was required.

There should be no serious objection to the use of a rear intake on landing since the reduction in thrust with the loss of the ram effect under these conditions would not be important. In fact it may be of some value because "thrust spoiling" by means of deflectors at the end of the jet pipe of a gas turbine is being considered for landing on an aircraft carrier deck. However, the loss of total pressure at the engine intake when the rear slots are brought into use may affect the operation of the turbine and the change over from forward to rear intakes may cause surging of the compressor, particularly if an axial compressor is to be used.

It is known that any form of brake must have as little effect as possible on trim on landing and that ordinary controls must operate[9]. The tail buffeting associated with the use of a parachute downstream of the tail may possibly be replaced by a buffeting on the aeroplane with a "Wake brake" scheme, even when the rear suction slots are fitted at the roots of the wing, which should be the best position to apply the braking force to an aeroplane.

The great thickness of the wake corresponding to the unstable flow is one of the features why a large drag force is obtained with a free rear stagnation point. It is doubtful however, whether a high tailplane would

help to maintain the use of conventional controls because it would be difficult to position the tailplane outside this wake. For example, Figs. 3 and 4 show the unstable flow from a 25 per cent. thick rear suction aerofoil when the flap is retracted to release the rear stagnation point. The unstable flow can be directed either upwards (Fig. 4) or downwards, but there are still disturbances in the flow producing changes in lift and drag and even with the tailplane on the opposite side to the wake, buffeting of the aeroplane may occur.

An additional item may be a division in the rear suction slot capable of vertical movement and rotation. This division would enable the wake of the unstable flow to be directed as required and also would exert some control on the magnitude of the lift. With the division nearer to the top of the slot a small negative lift could presumably be arranged for the wing, or at the least, a dangerous positive lift could be avoided, when the aeroplane was landing.

At this stage it is not clear at what part of the landing run the "Wake brake" should be brought into action. It would be soon enough, presumably, to start the brake when the landing wheels touch the ground and if necessary, to use normal air brakes as the aeroplane makes its landing approach.

3. CONCLUSIONS

(1) As far as can be ascertained from available data, any practical "Wake brake" scheme provides a greater drag force for braking on landing than the release of a 7 ft. diameter parachute behind the aeroplane.

(2) For (1), the suction quantity is always high and at least one large gas turbine must be connected to the rear suction slots of a 25 per cent. thick wing. For thinner wings, a bleed from the slots to the turbine should be enough.

(3) With thinner wings the rear slots are rather long unless the landing speed is high.

(4) Rear suction can be used on landing because the reduction in thrust with the loss of the ram effect is not important.

(5) One parachute can only be used once per flight whereas a "Wake brake" can be switched off (by changing over the valves in the suction supply) and used as many times as required.

4. SUGGESTIONS FOR FUTURE DEVELOPMENTS

(1) Wind tunnel tests are suggested on thinner wings with rear suction slots to assess how the wake drag coefficient and suction quantity coefficient vary in practice with thickness/chord ratio.

(2) An investigation of the stability of an aeroplane on landing, using rear suction slots at the roots of the wing is recommended.

(3) A wind tunnel experiment should be made on a complete model with a brake scheme, similar to that suggested in this note, to determine the drag available for landing.

ACKNOWLEDGMENTS

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The Reynolds Analogy Applied to a Cylinder Rotating in Air

by

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WHEN a turbulent fluid flows past a solid surface whose temperature differs from that of the fluid, the shear stress at the surface and the heat flow from it can be related by means of the Reynolds analogy. This analogy has been improved by Prandtl, Taylor, von Kármán and others, and its validity has been tested for flow through tubes and past flat plates by several investigators. In this note the analogy is checked against shear stress data[1] and heat transfer data[2,3] for a cylinder rotating in "still" air, when the flow is turbulent.

Received 2nd January 1954.

NOTATION

c_p specific heat
d cylinder diameter, characteristic dimension
k thermal conductivity

n rotational speed
q heat flow per unit area and unit time
t temperature
u fluid velocity in x-direction
x, y co-ordinates
α thermal diffusivity $(=k/\rho c_p)$
ε eddy diffusivity
μ dynamic viscosity
ν kinematic viscosity $(=\mu/\rho)$
ρ density
τ shear stress

Dimensionless Groups

Nu Nusselt number $(=qd/k(t_s-t_w))$
Pr Prandtl number $(=c_p\mu/k)$
Re Reynolds number $(=\rho u_s d/\mu)$
f friction factor $(=2\tau_w/\rho u_s^2)$
u^* ratio of local velocity to friction velocity $(=u/\sqrt{(\tau_w/\rho)})$
y^* the ratio $y\sqrt{(\tau_w/\rho)}/\nu$

Subscripts

b edge of laminar sublayer
s free stream
w wall

1. BRIEF STATEMENT OF THE THEORY

When a fluid flows past a surface with a free stream velocity u_s, the shear stress along a surface 1-1 in the boundary layer (Fig. 1), where $u < u_s$, can be written as

$$\tau = \mu\left(\frac{du}{dy}\right) + \rho\varepsilon\left(\frac{du}{dy}\right) = \rho(\nu+\varepsilon)\left(\frac{du}{dy}\right). \qquad (1)$$

The rate of heat flow across unit area 1-1 can be written as

$$q = -k\left(\frac{dt}{dy}\right) - \rho c_p\varepsilon\left(\frac{dt}{dy}\right) = -\rho c_p(\alpha+\varepsilon)\left(\frac{dt}{dy}\right). \qquad (2)$$

An assumption implied in equations (1) and (2), usually accepted as approximately correct in the development of the simple theory, is that the shear stress $\rho\varepsilon(du/dy)$ due to the eddy momentum exchange across 1-1 can be expressed in terms of the same coefficient ε as the heat transfer $\rho c_p\varepsilon(dt/dy)$ resulting from the same eddy motion. It must be emphasised that, even though ε is assumed the same for shear stress and heat transfer at any one section, ε varies with the distance y from the wall. In the thin laminar sublayer, where there is no eddy motion, $\varepsilon = 0$ and the velocity and temperature profiles are linear. Outside the sublayer ε varies, and the velocity and temperature profiles are curved (Fig. 1).

Equations (1) and (2) can be written as

$$du = \frac{\tau dy}{\rho(\nu+\varepsilon)}, \qquad (3)$$

$$dt = -\frac{q dy}{\rho c_p(\alpha+\varepsilon)}. \qquad (4)$$

It is required to find the relation between shear stress τ_w and heat flow q_w at the wall, in terms of some convenient reference velocities and temperatures, and therefore it is necessary to integrate equations (3) and (4)

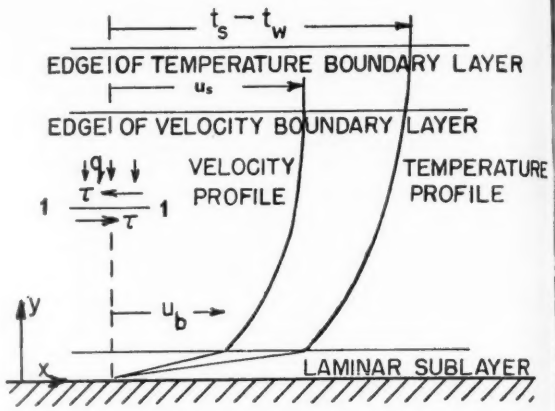


FIGURE 1. The turbulent boundary layer.

between limits of y corresponding to the selected reference planes. Usually the velocities and temperatures in the free stream and at the wall are known. Integrating equations (3) and (4), and dividing one by the other, the following relation is obtained:—

$$\frac{u_s - u_w}{t_w - t_s} = \frac{u_s}{t_w - t_s} = \frac{\int_w^s \frac{\tau dy}{\rho(\nu+\varepsilon)}}{\int_w^s \frac{q dy}{\rho c_p(\alpha+\varepsilon)}}.$$

A further assumption made is that q and τ vary similarly with y[5], and hence

$$\frac{u_s}{t_w - t_s} = \frac{\tau_w c_p \int_w^s \frac{\tau dy}{\rho(\nu+\varepsilon)}}{q_w \int_w^s \frac{\tau dy}{\rho(\alpha+\varepsilon)}}. \qquad (5)$$

The ratio of the integrals in equation (5) can be put equal to unity provided $\alpha = \nu$, *i.e.* $Pr = 1{\cdot}0$. Thus the equation

$$\frac{u_s}{t_w - t_s} = \frac{\tau_w c_p}{q_w}, \qquad (6)$$

expressing the simple Reynolds analogy, is obtained.

To extend the validity of the theory to fluids of Prandtl numbers between 0·5 to 2·0, Prandtl and Taylor adopted the following procedure. The boundary layer

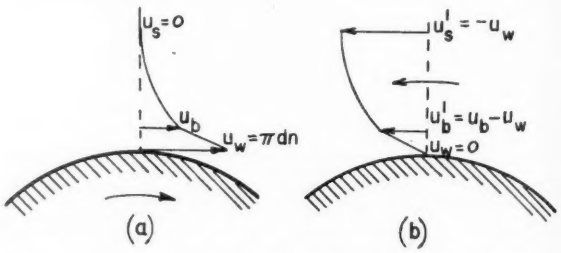


FIGURE 2. The absolute velocities in the boundary layer (*a*), and the velocities relative to the cylinder surface (*b*).

is divided into two regions. First, a thin laminar sublayer in which $\varepsilon=0$, and within which

$$\tau=\rho\nu\left(\frac{du}{dy}\right), \quad \text{and} \quad q=-k\left(\frac{dt}{dy}\right).$$

Second, a turbulent layer in which both ν and α are much smaller than ε, that is in which $(\nu+\varepsilon)\simeq(\alpha+\varepsilon)$. It can then be shown that

$$\frac{u_s}{t_w-t_s}=\frac{\tau_w c_p}{q_w}\frac{1}{1+\frac{u_b}{u_s}(Pr-1)}, \quad . \quad (7)$$

where u_b is the velocity at the edge of the laminar sublayer. This relation can be put into dimensionless form as

$$Nu=\frac{f}{2}\frac{RePr}{1+\frac{u_b}{u_s}(Pr-1)} \quad . \quad . \quad . \quad (8)$$

For fluids of Prandtl number much larger than unity this theory does not agree well with experiment; this is because between the laminar sublayer and the fully turbulent layer there is a transitional buffer layer for which the assumption $(\nu+\varepsilon)\simeq(\alpha+\varepsilon)$ does not hold. Von Kármán improved on the Prandtl-Taylor theory by allowing for such a buffer layer. A good review of existing theories is found in Refs. (4) and (5).

The heat transfer data discussed in the next section apply to a cylinder rotating in air. For air $Pr=0{\cdot}70$, and the Prandtl-Taylor relation (8) is considered to be sufficiently accurate.

2. THE APPLICATION OF THE ANALOGY TO A CYLINDER ROTATING IN AIR

The Reynolds analogy can be applied to a rotating cylinder in the following way. The absolute surface velocity u_w is πdn, and the absolute free stream velocity u_s is 0 (Fig. 2(*a*)). It is the velocities relative to the cylinder surface which are relevant, and these, denoted by dashed symbols, are $u_w'=0$, and $u_s'=-u_w$ (Fig. 2(*b*)). The velocity at the edge of the sublayer, relative to the cylinder surface, is $u_b'=(u_b-u_w)$. It is evident from the derivation of equation (8), that the ratio u_b/u_s in that equation must be replaced by the ratio u_b'/u_s', and hence

$$Nu=\frac{f}{2}\frac{RePr}{1+\frac{u_b'}{u_s'}(Pr-1)} \quad . \quad . \quad . \quad (9)$$

The ratio u_b'/u_s' can be found from the universal velocity profile of a turbulent boundary layer, represented in terms of the dimensionless parameters u^* and y^* (Fig. 3). Three regions can be distinguished:—(*a*) the laminar sublayer, $u^*=y^*$, (*b*) the buffer layer, $u^*=-3{\cdot}05+5{\cdot}00\log_e y^*$, and (*c*) the turbulent layer,

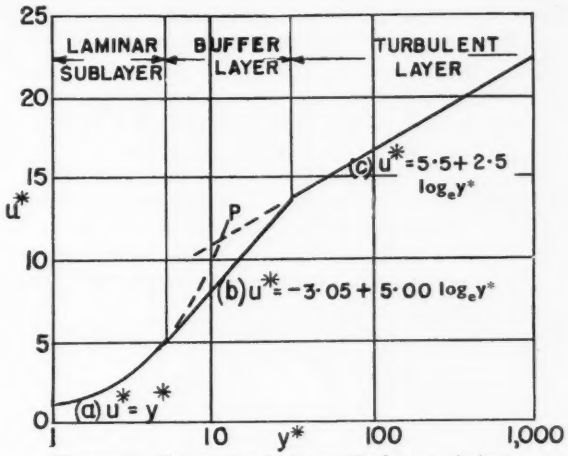
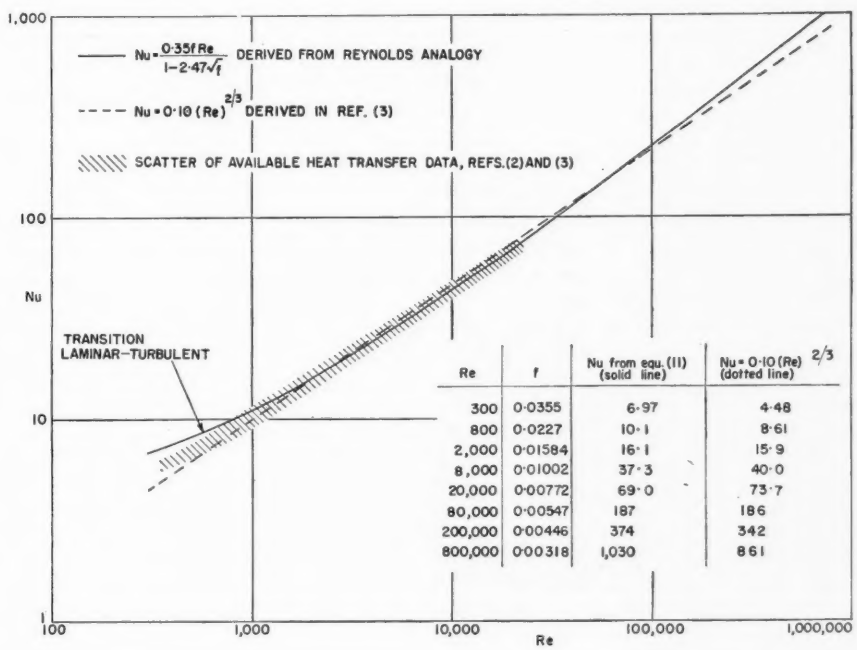


FIGURE 3. Universal velocity profile for a turbulent boundary layer.

The ratio u_b'/u_s' can be found from the universal velocity profile of a turbulent boundary layer, represented in terms of the dimensionless parameters u^* and y^* (Fig. 3). Three regions can be distinguished:—(*a*) the laminar sublayer, $u^*=y^*$, (*b*) the buffer layer, $u^*=-3{\cdot}05+5{\cdot}00\log_e y^*$, and (*c*) the turbulent layer,



Re	f	Nu from equ. (11) (solid line)	Nu = 0·10 (Re)^2/3 (dotted line)
300	0·0355	6·97	4·48
800	0·0227	10·1	8·61
2,000	0·01584	16·1	15·9
8,000	0·01002	37·3	40·0
20,000	0·00772	69·0	73·7
80,000	0·00547	187	186
200,000	0·00446	374	342
800,000	0·00318	1,030	861

FIGURE 4. Comparison of heat transfer data predicted from Reynolds analogy with experimental results.

$u^* = 5{\cdot}5 + 2{\cdot}5 \log_e y^*$. For air $Pr = 0{\cdot}70$, and it is sufficiently accurate to consider two regions only, *i.e.* a laminar sublayer and a turbulent layer. The co-ordinates of the edge of the sublayer are then given by the intersection of curves (*a*) and (*c*) at *P*, shown dotted in Fig. 3. Thus the co-ordinates of *P* are given by

$$u^* = y^* = 5{\cdot}5 + 2{\cdot}5 \log_e y^*,$$

and hence

$$u^* = y^* = 11{\cdot}6.$$

The ratio u_b'/u_s' in equation (9) can now be written

$$\frac{u_b'}{u_s'} = \frac{u_b'/\sqrt{(\tau_w/\rho)}}{u_s'/\sqrt{(\tau_w/\rho)}} = 11{\cdot}6\sqrt{\left(\frac{\tau_w}{\rho u_s'^2}\right)} = 11{\cdot}6\sqrt{\left(\frac{f}{2}\right)} = 8{\cdot}24\sqrt{f}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Substituting (10) in (9) and putting $Pr = 0{\cdot}70$, the expression for the Nusselt number becomes

$$Nu = \frac{f}{2}\,\frac{Re\,0{\cdot}70}{1 + 8{\cdot}24\sqrt{f}\,(0{\cdot}70 - 1)} = \frac{0{\cdot}35 f Re}{1 - 2{\cdot}47\sqrt{f}}. \quad (11)$$

Values of the friction factor f for a rotating cylinder can be calculated from

$$\frac{1}{\sqrt{f}} = -0{\cdot}6 + 4{\cdot}07 \log \frac{Re\sqrt{f}}{2} \quad . \quad . \quad (12)$$

according to Ref. (1). A few values of f and Nu have been tabulated in Fig. 4, and hence a curve of Nu against Re has been plotted on logarithmic scales. A shaded area, indicating the scatter of available experimental heat transfer data[2,3], is superimposed on this curve, showing the good agreement between the friction and heat transfer data. The equation $Nu = 0{\cdot}10\,(Re)^{2\cdot3}$, shown dotted in Fig. 4, is derived in Ref. (3) for calculating rates of heat transfer. It lies close to the solid line, derived from Reynolds analogy, only in the region of available heat transfer data, but it diverges from the solid line at higher Reynolds numbers.

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Terminal Delay Problems of the 130/150 Seater Jet Transport

by

WILLIAM COURTENAY, O.B.E., M.M., A.R.Ae.S.

THE LARGEST air transport at present operating on air routes is the Douglas Globemaster which is able to lift up to 130 passengers and a considerable load of mail and freight. Experience of flying Globemasters many times on the military route between Seoul City Airport (Korea) and Tashekawa Air Force Base (near Tokyo) suggests the following observations. They may be of value to those aircraft manufacturers in Great Britain now building 130/150 seater jet air liners and to British Overseas Airways Corporation and other air lines who will be concerned with operating them, possibly by 1960.

With the Globemaster, the large loads demand that passengers with their baggage assemble at the Air Force Base *three hours* before the advertised take-off time. To the 600 m.p.h. jet liner of 1960 this is the equivalent of an ocean crossing of 1,800 miles.

If *three hours* will be required to "process" and embark civil passengers in British or American 130/150 seater jet liners, will not a new form of "Terminal Delay" arise by 1960? Terminal Delay is usually associated with the vexed problem of the time consumed in conveying passengers from crowded city centres to distant airports. This problem should be solved by 1960 if the 50-seater Helicopter is available in large numbers with alighting sites in city centres. This time will be cut to about 15 minutes.

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Is not Terminal Delay going to be associated instead with the time consumed in processing a queue of 130/150 passengers waiting for take-off of a 600 m.p.h. jet liner? With the Globemaster, the loads are mostly of military personnel. These can be badgered, disciplined, marshalled, controlled and generally "pushed around" if necessary, to quicken the pace of movement. Not so the civilian who has paid a fare. Moreover, the Globemaster passengers do not have to be badgered by officialdom fussing round them about passports, visas, customs, health, immigration, or currency. Yet all of this must befall the hapless civilian, contributing considerably to delay.

How are the three hours consumed in the case of the Globemaster? Passengers are ordered to report at the Air Base Passenger Terminal by 11.30 hours each morning—for a take-off advertised for 14.40 hours—over three hours later. Between 11.30 and noon the passengers with their baggage crowd round the counter while their names are entered in a Manifest. It takes all of an hour at least to make up the Manifest for so large a number.

Baggage must be weighed and labelled and an hour or 90 minutes are required to load baggage, and so on, under the watchful eye of the Load master aboard the aircraft, for he will be responsible for the disposing of the loads.

There will always be last minute changes in passenger lists involving much erasing and completion of Manifests and weights.

At 13.00 hours the roll call must take place—usually in competition with the " noises off " of jet-engined aircraft in the vicinity and other noises inevitably associated with busy airfields. Many do not hear their names being called the first time; some have wandered away to check kit, or to buy a magazine. Civilians will be much worse. By 13.30 hours at the earliest—and it requires all of 30 minutes as a minimum—the roll call is complete.

Passengers have now to be marshalled with their hand baggage near the aircraft—a 15 minute task and walk—and at 14.00 hours embarkation begins. Each name must be checked against the Manifest as the passenger enters the aircraft, for there is a real risk of stowaways and of undisclosed weights aboard such large aircraft.

It takes all of 15 minutes for the long crocodile of 130 passengers to wind slowly into the aeroplane; to mount the stairs to fill the top deck first and then to fill the lower deck.

By 14.15 hours all may be seated and strapped in. " Cockpit drill " now begins and this is almost a mystic rite and a religious ceremonial for this big aircraft. All of 30 minutes will be required for this before the aircraft is ready at the end of the runway for the take-off signal. If the aeroplane is on time the Globemaster will be at the end of the runway with engines idling waiting for ten minutes for the take-off signal. At 14.40 the aircraft begins to roll down the runway.

No time has really been wasted—except by passengers who reached the field at 11.30 hours and whose particulars were all entered on the Manifest by noon. These early birds will have left Seoul at 11 a.m., or at 10.45 a.m., so that up to four hours Terminal Delay is really involved from the moment of leaving the city to the moment of take-off—enough for a 2,400 miles flight from London to Canada, in the 600 m.p.h. jet liner.

How then is the Air Line Operator (who has to marshall his passengers and prepare a Manifest and who, in addition, has to ensure that they are processed by Immigration, Medical, Currency, and Customs controllers) going to cut down this vexed, irritating period of grounding? If he cannot do so he will find flight in these 130/150 seater aeroplanes unpopular and may find they are left as white elephants on his hands. The public will not brook terminal delays of from three to four hours when air travel is offered them at 600 m.p.h.

It is suggested that in 1954 I.A.T.A. should set up a special committee to frame recommendations to I.C.A.O. on the matter. As it will require all of two years for all the Member States of I.C.A.O. to ratify any agreements reached by the Operators during 1954, it will be the end of 1956, or even 1957, before all Governments have agreed to a common policy. By 1958 the first of the 130/150-seater jet liners may be available. It is not too soon for I.A.T.A. to study the matter and draw up an Agenda for discussion by a special committee in 1954. Perhaps B.O.A.C. ought to take the initiative since they will be the first world operator using a really big jet air liner.

While these air liners are in early design stage it is suggested that aircraft manufacturers should give consideration to planning a " baggage room " aboard their jet liners so that baggage may be easily " getatable " and inspected during flight. For this is of the essence of the following proposals for I.A.T.A.

Other things being equal the manufacturer whose aircraft internal layout provides for the "baggage room " may have a superior selling point. If I.A.T.A. and I.C.A.O. are able to secure adoption of the following proposals then the jet liner without a baggage room may be the one rejected by the airline operators.

The ideal to aim at for 1960 should surely be this. The passengers and baggage are embarked in helicopters in city centres and 15 minutes later are set down beside the jet liners. They embark immediately, and within 30 minutes of their arrival at the airport the aircraft is airborne. Terminal Delay will still have consumed up to 60 minutes, since up to 15 minutes will be required to embark the passengers in two or three helicopters, get them airborne and on course to airports. Terminal Delay may thus never be less than 60 minutes for the 130/150-seater air liner or for larger types. It ought never to be more.

I.A.T.A. should press for the following internal arrangements:—

1. Passengers to be treated impersonally and given a small ticket like a railway ticket.
2. The onus of informing relatives of plans for flying to be cast upon the passengers; the Company not to be troubled with making up passenger lists or with all of the work and unproductive staff associated with the task.
3. Customs and Immigration Officials—if still needed—to be carried aboard every flight; their fares to be paid by their respective Governments.
4. Examination of tickets, passports, and so on, to be done aboard *after* take-off, since with proper control of gangways, and so on, it should be impossible for strangers without tickets to embark.
5. Passengers to be warned beforehand that if their papers are not in order during the flight they will be returned to the starting point at their own expense as soon as they reach the destination. Thus the onus is thrown on the passenger.
6. Jet liner flights will rarely last less than three hours or more than seven. Atlantic flights will be by daylight, as the period of flight will be too short for sleep. Thus each passenger during flight could attend the Customs and Immigration Official in the baggage room where all baggage and documents could be examined, and if a Manifest or passenger list is required at the port of destination it can be made up during the flight.
7. On arrival the passenger steps direct from the air liner to a waiting helicopter for the journey to town, his baggage following by road or helicopter to his hotel. He will have paid all Customs dues on board and will have had his passport stamped so that he will be as free to go ashore as if he had passed through the barriers on arrival after " processing."

8. Disembarking 130/150 passengers, loading them into waiting helicopters, flying them downtown, disembarking them in a city centre, will occupy at least an hour even without any waiting. It will become a disastrous three hours if all of the controls have to be passed through after landing and if another 130 seater—full of passengers—has just discharged them five minutes earlier. That makes a queue of 260. Or more if the air liner is a 150 seater.
9. Under this plan operators will also solve the growing vexatious problem of wasteful use of fuel in taxying to and from runways and airport aprons; the cost; the blast from jet engines on persons and equipment around the Passenger Terminal; damage to ground; and noise nuisance around busy offices.
10. The air liner on completing its pull up at the end of a runway should move to a hard stand or dispersal bay; several of these should exist on both sides of the runways. Thus runways would be clear at all times; the incoming air liner would move but a few yards from runway to dispersal bay—under its own power. Engine blasts would be over waste grass, far from the terminal buildings. Helicopters could alight beside the hard stands and passengers and crew, baggage and mail could be moved either by helicopter or by aerodrome vehicles. All waste taxying would be ended.
11. After disembarkation the jet liner would be towed to nearby hangars for its routine inspections or overhauls. The apron would cease to be used as an assembly area for take-off and all the waste taxying between runways and aprons would be ended.
12. Unless some such plan is prepared in 1954 and approved by all operators and ratified by all Governments by 1957 we shall be confronted with a new form of Terminal Delay of from three to four hours with these really big aircraft; we will be overwhelmed at first with the volume of traffic. After that the public will desert them for the smaller type of air liner and repeat the growing, demanding cry *"If you have time to spare, go by air."*

THE LIBRARY

Reviews

INTRODUCTION TO DYNAMICS. *L. A. Pars. Cambridge University Press, 1953. 512 pp. 31s. 6d. net.*

By any standards this is an impressive book. It represents a great amount of work by the author, and is probably the best book on elementary dynamics in the English language. Its scope may be defined as the study of the two dimensional motion of a particle, a rigid body, and a system of particles or rigid bodies—without Lagrange's equations.

The book is very clearly written, and is essentially an exposition of dynamics and a branch of Natural Philosophy, *not* a guide—of which there are plenty—on how to solve examination questions on dynamics. The extent to which vector notation is used will not satisfy the enthusiasts but is probably about right, and the last chapter in the book—on dimensions—includes matter which is all too often omitted from books on dynamics. The desirability of coining new words, e.g. Kineton (p. 32), is more questionable, and the discussion of Newton's Laws (p. 33) scarcely meets the difficulties of their logical status.

The production is excellent, and the publication price of 31s. 6d. for a book of 500 pages should ensure a wide circulation. It is, however, much to be hoped that the author will now follow this book up with another dealing with the more advanced parts of the subject, and it is here where the gap left by existing publications is greatest.

—D. M. A. LEGGETT.

THE ADVENTURE OF SPACE TRAVEL. *G. V. E. Thompson. Dobson, 1953. 253 pp. Diagrams and photographs. 10s. 6d. net.*

SPACE TRAVEL. *Kenneth W. Gatland and Anthony M. Kunesch. Wingate, 1953. 205 pp. Diagrams and photographs. 15s. net.*

MAN IN SPACE. *Heinz Haber. Sidgwick & Jackson, 1953. Diagrams. 291 pp. 30s. net.*

MAN ON THE MOON. *Edited Cornelius Ryan (text by Ley, von Braun and Whipple, illustrations by Bonestell, Klep and Freeman. Sidgwick & Jackson, 1953. 134 pp., 10 in. by 7½ in. Diagrams and colour plates. 25s. net.*

FLIGHT INTO SPACE. *Jonathan Norton Leonard. Sidgwick & Jackson, 1953. 245 pp. 12s. 6d. net.*

The flood of books on space-flight and related matters flows on unchecked. All the works concerned continue to be on the popular or semi-popular level, the publishing world having apparently decided that it is the considerable public interest in the subject which must be served. The number of people with a really deep technical interest in astronautics would apparently not yet constitute a worthwhile market. Alternatively (and very probably) its intimate association, in these early stages of its development, with guided missiles, high-speed aircraft, atomic energy, and other manifestations of the modern world of secret science, would preclude the preparation of any really satisfying volume for such an audience.

Many of the books which do appear are hardly worthy of serious notice, and of some, even more unkind things might be said. However, all five of those listed above have merit of one sort or another.

The first two are by leading members of the British Interplanetary Society. Thompson's book is a somewhat stolid, but accurate and lucid, introduction to the subject for the older and more serious teen-ager. For readers of this class with more than a passing interest in the subject it should be an excellent source of information. The Gatland/Kunesch volume is obviously designed to satisfy a similar need for scientifically-inclined adult readers (though many youngsters would soon graduate to it after reading Thompson), and again it succeeds very well. It is more thorough than most previous books in this class (in fact, it often shows the same plodding determination to leave nothing out that characterises Thompson's style), and it includes considerably more detailed technical discussion of the probable techniques of space-flight than any previous semi-popular work on the subject.

" Man in Space " is of American origin, and discusses the physiological and psychological hazards which will be faced in space-flight—a subject already described as " Space Medicine " in the States, where the author has been one of a small official group working on its problems. Dr. Haber believes that the final useful goal of space-flight, at any rate for a very long time to come, will be the construction of artificial satellite rockets and space stations, rather than true interplanetary travel. For this more limited objective, he shows some enthusiasm, qualified by a professional emphasis on the importance of his own subject in any efforts to attain it. His book is expensive and somewhat over-long (sometimes one feels the author is using a lot of words to say " We don't know . . ."), but it contains a great deal of interest.

The last two volumes on the list are perhaps the most important of the lot and are, in an indirect way, related.

" Man on the Moon," like its predecessor from the same authors and publishers (" Across the Space Frontier "), is an expanded reprint of a striking series of articles in the American " Collier's Magazine." The two volumes should really be studied together, in which form they represent a vivid presentation of the views on space-flight of its most eminent and vocal advocate, Dr. Wernher von Braun. This remarkable man was technically responsible for V.2, now holds a key position in the American missile programme, and has never made any secret of the fact that his real interest in rockets is for interplanetary travel.

The volume now under review is a popular description, supported by much technical data, of a proposal for a large-scale lunar expedition by a fleet of giant space ships, starting from a big satellite station, in the orbit of which they would be constructed, fuelled, and serviced with the aid of another fleet of huge winged rocket ships. Many interesting and important technical ideas are presented: for example, the use of low-acceleration flight techniques for the main journey, starting from an initial stable orbit outside the atmosphere, and the consequent design of the main vehicles with ultra-light structures and an absence of streamlining.

Most other astronautical thinkers would support von Braun in his advocacy of these features, but would criticise his overall schemes as being excessively ambitious, over-optimistic in terms of the time-scale and expenditure involved, and in some of the detailed technical estimates on which they are based. In short, they constitute a clear case of claiming we can run before we can do much more than crawl; however, there is no doubt that the Collier's articles and the resulting books represent a superficially

convincing account of von Braun's views, and one which will be very important historically. In the preparation of all these publications, von Braun has been well-served by a supporting team of able and well-qualified writers, and by three technical illustrators whose work has never been surpassed.

Jonathan Norton Leonard is the science editor of "Time," the American newsmagazine, and he has written "Flight Into Space" in the vivid, sophisticated, and highly-readable style for which this periodical is justly famous. The link with "Man on the Moon," already mentioned, lies in the fact that Leonard has rightly assessed the "expansive von Braun" as being "something of a prophet and something of a mystic," as well as being (surprisingly) a competent engineer. Much of the book therefore consists of a discussion of the "space crusade" which he is leading. A fair hearing is also given to the apprehensive views of more conservative workers in American rocketry, who apparently fear there is some risk of von Braun's succeeding in the diversion of funds to premature space-flight projects, at the expense of less-ambitious missile research of an earlier practical importance. Something very like this, it is suggested, happened in war-time Germany in connection with V.2. . . .

"Flight Into Space" is in no sense a technical book; it is science at its most popular but is none the less important. Its theme is best expressed by its own sub-title: "Facts, Fancies and Philosophy" (about space flight). Its merit lies partly in the shear skill of the author, partly in his early perception of important trends, but mainly in the fact that, unlike any previous books in the field, it is the objective work of someone outside it, rather than the special pleading of enthusiasts. Mr. Leonard has not refrained from indulging in some sly good humour at the expense of such people, but on the whole one is left with the impression that he has some considerable sympathy and belief in their aims.—A. V. CLEAVER.

JET: THE STORY OF A PIONEER. *Sir Frank Whittle, K.B.E., C.B., F.R.S. Frederick Muller Ltd., 1953. 320 pp. Illustrated. 16s. net.*

It would be difficult for anyone closely connected with the aero engine industry to review this book with impartiality. Indeed it is no easy task of discrimination for one who has merely watched the development of power plants, and the men who designed them, through a long period of wonderful achievement culminating in jet propulsion and speeds greater than sound.

The world is indebted to Frank Whittle for the opening of this latest vista, and has given evident expression of its gratitude and pride by the honours and rewards accorded him. It is, therefore, with something like dismay that the reader finds revealed in the pages of *Jet* the bitterness of the inventor's feeling at the treatment he received while endeavouring to bring to practical fruition his concept of the association of the gas turbine with jet reaction propulsion. But for his determination to turn the idea into reality the march of progress would have been delayed by a term of years, short or long, no man can guess—for it is probable that rival technicians, such as the Germans, may have been stimulated to jet engine research by Whittle's basic patent, published to the world as early as 1930. Certainly in this country his was the first practical jet engine built and run and flown in the face of what seemed discouraging apathy and even opposition.

The story of that struggle Whittle tells with disconcerting detail, naming those whom he believed frustrated him, and quoting from contemporary documents to support his theme that others were enabled to reap where he and his team had so tenaciously sought to sow.

In some ways it is reminiscent of the story of the Wrights, who enabled new conquest to be made by their scientific and practical ability, but who ultimately sacrificed irrevocable and ill-spared time in the endeavour to consolidate their invention with business interests and fought long and wearying law-suits to defend their patent rights against exploiters.

In his preface Whittle says: "This book is not auto-biography." Yet the story could hardly be more personal. It is no history of the evolution and establishment of jet power in general; instead it tells of the man and his struggle, not with science but with other men. Darkly one can perceive that this after all was not so much a battle of personalities as the warp and weft of many men's loyalties, each trying to find the best course in which to steer the genius of this great new invention within the complexity of world war planning.

When the late Mr. E. L. Pickles, on behalf of the Contracts Department of the Ministry of Supply, presented to the Royal Commission the case for an Inventor's Reward to Whittle he quoted from Shakespeare: "We wound our modesty and make foul the clearness of our deservings when of ourselves we publish them." So though there is no doubt that Sir Frank Whittle will stand forever with the immortals—with Watt and Faraday, with Marconi and the Wrights—one regrets that he should have unveiled to curious eyes this unhappy story of the past. He has no need of vindication.—HARALD J. PENROSE.

AIRBORNE AT KITTY HAWK. *Michael Harrison. Cassell & Co., 1953. 8s. 6d. net. Also Guild Books 2s. net.*

The only book published specifically for the Wright anniversary is a strange brief work by a good literary writer who does not care much for pedantic historical facts. He first gives a rapid survey of flying history before the Wrights; but when reaching the brothers does not even take them up to the historic year 1908, when they first flew in public.

I fear some of the mis-statements are rather serious for a historian. "Until the Wrights built their first successful machine, no one had investigated the properties of the aerofoil." "Pénaud . . . designed an aeroplane which incorporated such startlingly prophetic features as wing-warping" (he never even thought of the idea: Mr. Harrison is confusing it with Pénaud's famous auxiliary steering device). "A tail unit . . . with what we now call 'rudder' and elevator" (Mr. Harrison refers to these being used by Chanute before the Wrights: it was the other way round; Chanute copied them from the Wrights). "The wing-warping system of Pénaud had been adopted by such experimenters as Lilienthal, Pilcher and Chanute" (none of these men ever thought of warping; and Wilbur Wright got the idea from watching soaring buzzards).

The author implies that one of the Wright gliders had a "system by which the upper wing could be brought forward or backward in relation to the lower wing," whereas no such scheme was ever incorporated in any of their gliders. He says that no man-carrying glides were made with the 1900 glider: in fact twelve were made. He refers to "a small lateral (sic) 'elevator' in front of the glider." He says that "the ideal which was being forced on the Wrights was of a machine inherently stable," when the reverse is true. He says that the monorail launching track was to be used "only when the wind was blowing strongly," whereas the machine could not take off in any conditions without it, since wheels were not adopted by the

Wrights until 1909-10. He gives 45 m.p.h. as the speed of the first *Flyer*, instead of 30-31 m.p.h. as is well known and established. He implies that the original *Flyer* was the 1902 glider modified to take engine, etc., when it was a completely new machine which the brothers built and took to Kitty Hawk in 1903, along with the 1902 glider to practice on. Only 3 out of 33 illustrations show Wright aircraft, and one of them is wrongly captioned.

Finally, here is Mr. Harrison's strange account of Wilbur's historic and well documented failure of December 14th 1903:—

"The machine at last at the place selected, it was fastened with a wire stay to the rail, so that it could not fly away; and a trial 'flight' was made, with the motor running, and Orville Wright running alongside, steadying the wing. Unfortunately, the 'take-off' was so rapid that Orville lost control; the machine rose in the air; stalled, and then crashed to the bottom of the hill, a hundred feet from the starting point."—C. H. GIBBS-SMITH.

AN INTRODUCTION TO RELAXATION METHODS. *F. S. Shaw. Dover Publications Inc., 1953. 396 pp. $5.50.*

A new book on relaxation, the third in all and the first not composed by its originator, must attract the attention of all who want numerical results. Linear algebra is ubiquitous in computation, and the avowed aim of this book is to teach the beginner how to solve linear equations by relaxation, with little reference to their origin and no emphasis on practical problems.

For accurate and economic computation, however, this is not sufficient, as the author realised, but his selection and treatment of ancillary topics is not everywhere happy. It is good to remark on the distinction between initial-value and boundary-value problems, but parabolic equations, here not treated, can be "relaxed" in two ways. Non-linear equations are not mentioned, and the useful "deferred approach to the limit" method ignored. The difference in precision between results obtained for second-order and fourth-order equations, and also for different numbers of mesh points, is rightly observed, but the corresponding effects of different boundary conditions is hardly mentioned. Correctly stressing the difficulty of relaxing ill-conditioned equations, he also mistrusts direct methods, apparently as a result of a piece of computation which this reviewer finds incorrect. In Chapter III the first table of differences does not conform to later definitions, statements on the neglect of higher differences on pages 67 and 69 are misleading, and footnote (16) is quite wrong. The tables at the end lack facilities for interpolation.

Nevertheless the book has generally succeeded in its attempt to teach processes of liquidating residuals, and in this sense it fills a gap left by its predecessors. The chapters on differential equations are particularly good.

After an introduction outlining the origin of the name, Chapter I discusses the fundamentals of the process for solving general systems of linear algebraic equations, its vocabulary and devices for accelerating the convergence of this method of successive approximation. Chapter II obtains, by various methods, finite-difference formulae for derivatives, integrals and differential operators preparatory to the solution, in Chapters III to VII, of ordinary and partial differential equations of orders two and four. Chapter VIII is devoted to eigen-value problems for general matrices and differential equations. Chapter IX indicates briefly the treatment of free surface problems, integral equations, methods for improving accuracy for differential equations, and the advantages of non-dimensional treatment. There are extensive tables of Lagrangian coefficients for derivatives and finite-difference expressions for use near curved boundaries, and a bibliography of papers on relaxation, arranged chronologically and covering the period 1935-1949. Numerous worked examples illustrate the text.

The many diagrams are beautifully drawn and lettered, but there are not a few misprints and typographical blemishes. For a book produced by photography of typed material, the price seems excessive.—L. FOX.

FASTER THAN THOUGHT. *Edited by B. V. Bowden. Pitman, London, 1953. 416 pp. illustrated. 35s. net.*

It was said of an earlier book—a good one—on this topic, that the worst thing about it was its title. This cannot be said of the present book, as inspection of the "Glossary" will reveal. The apparently catch-shilling title is quite a fair description of how far too much of it was written or, more likely, dictated.

The historical part of the first chapter, called "A Brief History of Computation," is so brief that it has to omit the history of computation. It then makes two fundamentally false assertions about the relation between "analogue" and "digital" calculators, depending on a confusion between "accurate" and "distinguishable." Thus is dismissed the only chance in the whole book to analyse what makes a computer a transformer of language rather than a cud-chewing mechanism. It is with the last that the book is primarily concerned.

The Oriental Abacus ("bead-frame") and desk machines are dismissed in one page—one half the space given to the breeding of race-horses. The wired abacus did not reach Europe till 1812, via Russia, but Dr. Bowden has managed to identify it with the forms of abacus used in Europe for millenia. The "abaci" attributed to Gerbert were not computing devices, but computing algorithms.

Two paragraphs containing the names of Pascal, Leibniz, and Odhner cover the history of desk calculators which, apparently, culminates in the Brunsviga. Thomas de Colmar, Chebyshef, Hamann, and Baldwin are not mentioned, and some startling statements about desk computation do not suggest much personal experience of this activity. Napier's binary multiplier, the numerous patents of the last few decades, and the binary machines of the 1930's by Phillips in England, Couffignal and Valtat in France, are ignored. They were not electronic. Perhaps the printing of "Repression" for "Regression" in Chart 3 has some deep significance?

Dr. Bowden would have been wiser just to refer readers to standard texts such as Baxandall, Cajori, Dyck, d'Ocagne, and D. E. Smith, but even in the References the race-horses lead by a head. There is no compulsion on anyone to give tongue on matters outside his speciality, and too often the reader will be reminded of the candidate for scriptural honours who, when asked "Who was the first king of Israel?", answered "Saul," hastily adding in the flush of victory, "afterwards known as Paul."

The part about Babbage, though grossly inflated with irrelevancies, is sounder, but has some major errors. The greatness of Babbage as mathematician, computor, and pioneer of "scientific management" (not "operational research") has been recognised for a long time. There is no need to give him the priority due to J. H. Mueller for suggesting in 1786 automatic machinery for table-making by summation of differences. Nor need he be credited with the Scheuz'-Donkin "Mark II." Inspection

of even photographs would alone show that its mechanism, and its predecessor's, owe nothing to Babbage.

A worthwhile item is the reprint, free of editorial chatter, of Lady Lovelace's translation of and comments on Menabrea's discussion of the Analytical Engine.

The section on computer components sensibly advises the electronically innocent reader to skip it; but then gives a rather eyebrow-raising explanation of diodes and triodes followed by sophisticated terms left unexplained. Boolean algebra is dragged onstage by the tail and left lying there.

The central section of the book describes the Manchester University Computer in full, and various writers describe other actual and projected British machines. These descriptions are rather concise, and are aimed at different types of reader. A short chapter lists the major U.S.A. projects at the time of writing. Today there is some hope that The Emperor's New Clothes era of computer construction is closing.

A number of experts, one or two of whom have been granted this status at rather short notice, then write about various applications, actual and speculative, of high speed computers. These chapters are unco-ordinated and, once more, aimed at different types of reader.

The chapter on solution of logical problems is based on already published articles, but has been improved, particularly by reparation for a previous injustice to Jevons. The specialist may find that it leaves off just when he would like to hear more; for instance, about the method of finding a single distribution satisfying a disjunctive normal form. The general reader may be misled by over-concise statement; *e.g.* the bare assertion that "not both" and "neither" are unique primitive binary relations may obscure the possibility of primitive relations between more than two variables. The authors might profitably have reminded readers that the "logic" dealt with by computers is very restricted in relation to the scope of Symbolic Logic, even more to that of the "logic" of ordinary discourse.

A section called "Thought and Machine Processes" could contain anything, and does its best to. In the main a concatenation of quotations, it does give some details of the mental calculation methods used by Professor A. C. Aitken and by Herr Klein. The fundamental issue, burked at the beginning of the book in the "analogue" and "digital" muddle, surfaces again when Bush's proposals for library mechanisms are exhumed. These beg the question, which is not the manipulation of marked objects, but the assignment and interpretation of these marks. Over fifty years ago Klein pointed out that calculating machines are mathematical notation. Their semantics must be supplied externally. Before computing comes mathematics, before mathematics comes understanding of the subject. High speed computers demand that engineers and physicists become better engineers and physicists. Only computors need become better computors.

Those of the contributors who have used computing as a means to an end know this, but the editor has not brought it out. The value of the book falls far short of the value of some of its parts, which are not improved by being bound up with garrulous error. Lord Halsbury, in his foreword, says that this publication has something for everybody. So has a secondhand bookshop, but there you can buy books separately.—R. A. FAIRTHORNE.

JANE'S ALL THE WORLDS AIRCRAFT 1953/4. *Compiled and edited by Leonard Bridgman. Sampson Low, Marston & Co. Ltd., London 1953. 400 pp. 84s. net.*

Every year the poor reviewer tries to say something new about "Jane's"—the number of pages devoted to Soviet aircraft; the renaissance of the Japanese Industry, the disappearance from the pages of some well-loved type—and what does it all boil down to? Either you need "Jane's" or you don't. There is no other book of its kind to take its place; there has never been a real attempt to produce a competitive volume and if such an attempt were made it would be abortive—even at four guineas.

The fact that each year the new "Jane's" is awaited with interest, combed through and every change noted and commented on by reviewers is a tribute to the reputation which first the late C. G. Grey and then Mr. Bridgman (who assisted in the preparation of "Jane's" for many years before becoming Compiler and Editor) have established for this unique publication.—F.S.

Additions to the Library

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* *Reference only.*

Reports

AERODYNAMICS

Boundary Layer

See also Internal Flow

Experiments on the flow past a porous circular cylinder fitted with a Thwaites flap. R. C. Pankhurst and B. Thwaites. R. & M. 2787 (*October* 1950, *published* 1953).

This paper describes wind-tunnel experiments on a porous circular cylinder of 3 in. diameter fitted with a Thwaites Flap. Measurements were made of the pressure distribution at mid-span, together with a number of wake traverses, over a range of suction quantity, flap size, wind speed and flap setting.—(1.15 × 1.4).

Some features of artificially thickened fully developed turbulent boundary layers with zero pressure gradient. P. S. Klebanoff and Z. W. Diehl. N.A.C.A. Report 1110 (1952).

Results are presented of tests to determine the feasibility of artificially thickening a turbulent boundary layer on a flat plate. It is shown that it is possible to do substantial thickening and obtain a fully developed turbulent boundary layer which is free from any distortions introduced by the thickening process. Measurements of mean velocity, spectrum of u-fluctuation, and intensity of u-fluctuation are presented. Some features of the fully developed turbulent boundary layer with zero pressure gradient are discussed.—(1.1.3).

Experimental investigation of the effects of cooling on friction and on boundary-layer transition for low-speed gas flow at the entry of a tube. S. J. Kline and A. H. Shapiro. N.A.C.A. Technical Note 3048 (*November* 1953).

The effect of cooling on boundary-layer transition in the steady flow of air in the entrance of a smooth round tube was investigated experimentally. Runs were made at diameter Reynolds numbers varying from 50,000 to 106,000. —(1.1.2).

An analytical investigation of the effect of the rate of increase of turbulent kinetic energy in the stream direction on the development of turbulent boundary layers in adverse pressure gradients. B. Rashis. N.A.C.A. Technical Note 3049 (*November* 1953).

A general integral form of the boundary-layer equation which includes the Reynolds normal-stress term is derived. Two special equations are obtained from the general form. They are the modified momentum equation and the modified kinetic-energy equation. In addition, the parameters which control the dissipation of mean-flow kinetic energy by the shearing stress and the Reynolds normal stress are suggested. —(1.1.3).

A flight investigation of laminar and turbulent boundary layers passing through shock waves at full-scale Reynolds numbers. E. N. Harrin. N.A.C.A. Technical Note 3056 (*December* 1953).

An investigation was made in flight at free-stream Mach numbers up to about 0·76 and Reynolds numbers up to about 26×10^6 to determine the behaviour of laminar and turbulent boundary layers passing through shock waves. Boundary-layer and pressure-distribution measurements were made on a short-span aerofoil built around a wing of a fighter aeroplane. The free-stream Mach numbers reached in the tests were sufficiently high to give extensive regions of local supersonic flow. Comparison is made with results of tests at low Reynolds numbers (up to 1/10-scale) of other investigations.—(1.1.0).

Effect of type of porous surface and suction velocity distribution on the characteristics of a 10·5*-percent-thick airfoil with area suction. R. E. Dannenberg and J. A. Weiberg. N.A.C.A. Technical Note* 3093 (*December* 1953).

Results are presented of an investigation of a two-dimensional, 10·51-per cent.-thick symmetrical aerofoil with area suction near the leading edge. Lift and suction-flow characteristics were determined with different porous surfaces (perforated plates and sintered steel) for various suction velocity distributions. The requirements were ascertained over a range of free-stream velocities.—(1.1.5).

A method for estimating the effect of turbulent velocity fluctuations in the boundary layer on diffuser total-pressure-loss measurements. J. Persh and B. M. Bailey. N.A.C.A. Technical Note 3124 (*January* 1954).

A method has been devised for estimating the effect of turbulent velocity fluctuations on diffuser total-pressure-loss measurements. In the development of this method, continuity of flow is stipulated, and it is assumed that the inlet conditions and the diffuser dimensions are accurately known, that the flow is symmetrical, and that the velocity outside the boundary layer at the downstream measuring stations is not measurably influenced by turbulent velocity fluctuations. —(1.1.3 × 1.5.1).

Compressible Flow

Détermination de la vitesse critique par des calculs simplifiés. G. de Vries. O.N.E.R.A. Note Technique 16 (1953).—(1.2.2.). *Nouvelles applications de la méthode de Lighthill a l'étude des ondes de choc. J. Legras. O.N.E.R.A. Publication No.* 66 (1953).—(1.2.3 × 1.10.1.1).

*The pressure distribution on a body of revolution in a free jet at Mach number of unity. E. W. Graham and K. Walker, Jr. Douglas Report SM-*14913 (*September* 1953).

The flow about a smooth slender body of revolution at zero angle of attack in a sonic "free" jet is considered. (A "free" jet is one which has zero pressure on the boundary.) A second order theory is developed for such a flow by means of an iteration process. The magnitude of the second order terms shows that linearised theory rapidly becomes incorrect as the jet radius is increased. An approximate upper limit for the jet radius permitting valid linearised analysis is determined.—(1.2.3 × 1.6).

The linearized characteristics method and its application to practical nonlinear supersonic problems. A. Ferri. N.A.C.A. Report 1102 (1952).

The method of characteristics has been linearised by assuming that the flow field can be represented as a basic flow field determined by non-linearised methods and a linearised superposed flow field that considers small changes in boundary conditions. The method has been applied to two-dimensional rotational flow, to calculations of axially symmetric flow, to slender bodies without symmetry, and to wing problems.—(1.2.3 × 1.6 × 1.10.1.2).

Investigation at supersonic speeds of the wave drag of seven boattail bodies of revolution designed for minimum wave drag. A. F. Bromm, Jr., and Julia M. Goodwin. N.A.C.A. Technical Note 3054 (*December* 1953).

Results are presented from an investigation of the variation with Reynolds number and Mach number of the wave drag of seven boat-tail bodies of revolution designed for minimum wave drag according to the theory presented in N.A.C.A. T.N.2550.—(1.2.3 × 1.6).

Flow properties of strong shock waves in xenon gas as determined for thermal equilibrium conditions. A. P. Sabol. N.A.C.A. Technical Note 3091 (*December* 1953).

The results of calculations are presented for the purpose of showing the effects of ionisation and electronic excitation on the flow properties of one dimensional shock waves in xenon gas. The calculations use statistical-mechanics theory with the assumption that thermal equilibrium exists at all points in the flow. The calculations are made by both including and neglecting the effects of electronic excitation, and the results of the calculations are qualitatively compared with available experimental data.—(1.2.3.).

NOTE:—*The figures in parentheses at the end of each Summary are for office use only.*

Control Surfaces

Low speed wind tunnel tests on a new type of air brake suitable for Vampire aircraft. P. B. Atkins and R. W. Murphy. A.R.L. Australia. Aerodynamics Note 106 (*August* 1952).

A series of dive brakes suitable for direct installation in Vampire aircraft has been tested in a low-speed tunnel. The new brakes consist of banks of turning vanes which could be installed in place of the existing brake; the drag coefficient of the brake has been increased from 1·15 to 2·04 while the change in pitching moment is smaller than that for the normal type of brake.—(1.3.4).

Wind tunnel tests of a 0·30*c double slotted flap. G. A. Collins. A.R.L. Australia. Aerodynamics Note* 124 (*July* 1953).

A 0·30*c* double slotted flap on a 17 per cent. thick two-dimensional aerofoil has been tested in the wind-tunnel at a Reynolds No. of $2{\cdot}8 \times 10^6$. Lift and drag coefficients for various flap angles and incidences have been measured for both a smooth wing and a wing using raised-head riveted construction. Measurements of the flap hinge moment coefficient were also made.—(1.3.4 × 1.10.2.1).

Fluid Dynamics

See also Boundary Layer

Reciprocity relations in aerodynamics. M. A. Heaslet and J. R. Spreiter. N.A.C.A. Report 1119 (1953).

Reverse-flow theorems in aerodynamics are shown to be based on the same general concepts involved in many reciprocity theorems in the physical sciences. Reciprocal theorems for both steady and unsteady motion are found as a logical consequence of this approach.—(1.4).

The free-stream boundaries of turbulent flows. S. Corrsin and A. L. Kister. N.A.C.A. Technical Note 3133 (*January* 1954).

An experimental and theoretical study has been made of the instantaneously sharp and irregular front which separates turbulent fluid from contiguous "non-turbulent" fluid at a free-stream boundary. The overall behaviour of the front is described statistically in terms of its wrinkle-amplitude growth and its lateral propagation relative to the fluid as functions of downstream co-ordinate.—(1.4.).

Internal Flow

See also Boundary Layer

Preliminary investigation of a new type of supersonic inlet. A. Ferri and L. M. Nucci. N.A.C.A. Report 1104 (1952).

A supersonic inlet with supersonic deceleration of the flow entirely outside of the inlet is considered. A particular arrangement with fixed geometry having a central body with a circular annular intake is analysed, and it is shown theoretically that this arrangement gives high pressure recovery for a large range of Mach number and mass flow and, therefore, is practical for use on supersonic aeroplanes and missiles.—(1.5.1)

The resistance to air flow of porous materials suitable for boundary-layer-control applications using area suction. R. E. Dannenberg, J. A. Weiberg and B. J. Gambucci. N.A.C.A. Technical Note 3094 (*January* 1954).

Measurements have been made of resistance to air flow of commercially available porous materials. Three general types of porous media were tested—granular (sintered metals), fibrous (felt cloths and filter papers), and perforated. The flow-resistance characteristics were ascertained over a wide range of differential pressures across the material.—(1.5.1 × 1.1.5).

Loads

See also Compressible Flow

A method for calculating the subsonic steady-state loading on an airplane with a wing of arbitrary plan form and stiffness. W. L. Gray and K. M. Schenk. N.A.C.A. Technical Note 3030 (*December* 1953).

A method for computing the span load distribution on an elastic aeroplane wing at specified aeroplane weights and load factors is given. The method, which applies for sub-critical Mach numbers for wings of arbitrary plan form and stiffness distribution, includes the effects of external stores and fuselage on the spanwise loading. Modifications are outlined for treating tail-boom and tailless aeroplane configurations and for calculating the divergence dynamic pressure of a swept wing with a large external store.—(1.6).

Low-speed drag of cylinders of various shapes. N. K. Delany and N. E. Sorensen. N.A.C.A. Technical Note 3038 (*November* 1953).

An investigation has been conducted to find the approximate variation of the drag coefficient with Reynolds number of cylinders. Data were obtained for circular cylinders, elliptical cylinders of two fineness ratios, rectangular and diamond cylinders of three fineness ratios, and two isosceles triangular cylinders (apex forward and base forward). Three different corner radii were tested. Data were obtained for Reynolds numbers as low as 11,000 and high as 2,300,000. Frequencies of pressure fluctuations in the wake were measured for some of the cylinders.—(1.6).

A simplified mathematical model for calculating aerodynamic loading and downwash for wing-fuselage combinations with wings of arbitrary plan form. M. Zlotnick and S. W. Robinson, Jr., N.A.C.A. Technical Note 3057 (*January* 1954).

For the purpose of calculating the aerodynamic loading on the fuselage, the midwing wing-fuselage combination with a fuselage of circular cross section can be represented by a simple system of horseshoe vortices located on the wing with images located inside the fuselage. By using this simplified mathematical model, a method for calculating the lift and longitudinal centre of pressure on the fuselage in the presence of the wing at subsonic speeds is presented. —(1.6 × 1.10.1.2).

Stability and Control

The theoretical effect of flight path angle on the lateral stability and response of an aircraft. E. M. Frayn and M. V. Parnell. R. & M. 2529 (*November* 1945, *published* 1954).

The response of a typical aircraft of the dive-bomber class to various disturbances has been calculated at four angles of dive covering the range 0 to 90 deg. and for four pairs of values of l_v, n_v. The most notable effect on stability is the marked increase in spiral damping with increasing dive angle at the same T.A.S. This has little effect on the response, since in most components, this mode is scarcely excited.—(1.8.1).

*Scale effect on spinning of a delta wing. A. V. Stephens and V. J. Smith. A.R.L. Australia. Report A.*84 (*September* 1953).

Measurements of spinning moment were made on a delta wing mounted on a rolling balance in the 7 ft. × 5 ft. wind tunnel at Sydney University over a range of Reynolds number extending upwards from that commonly occurring in free model spinning experiments.—(1.8.3).

Theoretical and experimental investigations of interference effects of delta wing—vertical tail combinations with yaw. Willi Jacobs. FFA, Sweden. Report No. 49 (1953).

The interference effects between vertical tail and delta wing with yaw are investigated theoretically and experimentally. The experiments include force and pressure measurements with a delta wing with a 70° swept-back leading edge and three different vertical tails, two single vertical tails with different sweep angles and a double vertical tail.—(1.8.1).

Summary of methods for calculating dynamic lateral stability and response and for estimating lateral stability derivatives. J. P. Campbell and Marion O. McKinney. N.A.C.A. Report 1098 (1952).

A summary of methods for making dynamic lateral stability and response calculations and for estimating the aerodynamic stability derivatives required for use in these calculations is presented. The processes of performing calculations of the time histories of lateral motions, of the period and damping of these motions, and of the lateral stability boundaries are presented as a series of simple straight-forward steps. Existing methods for estimating the stability derivatives are summarised and, in some cases, simple new empirical formulas are presented. Detailed estimation methods are presented for low-subsonic-speed conditions but only a brief discussion and a list of references for transonic- and supersonic-speed conditions.—(1.8.1).

Experimental determination of the effect of horizontal-tail size, tail length, and vertical location on low-speed static longitudinal stability and damping in pitch of a model having 45° sweptback wing and tail surfaces. J. H. Lichtenstein. N.A.C.A. Report 1096 (1952).

An investigation has been conducted in the Langley stability tunnel to determine the effects of horizontal tails of various sizes and at various tail lengths (when located on the fuselage centre line) and also the effects of vertical location of the horizontal tail relative to the wing on the low-speed static longitudinal stability and on the steady-state rotary damping in pitch for a complete-model configuration. The wing and tail surfaces had the quarter-chord lines swept back 45° and had aspect ratios of 4.—(1.8.2).

Theoretical calculations of the effects of finite sideslip at supersonic speeds on the span loading and rolling moment for families of thin sweptback tapered wings at an angle of attack. W. L. Sherman and Kenneth Margolis. N.A.C.A. Technical Note 3046 (*November* 1953).

By means of the expressions derived in N.A.C.A. Technical Note 2898, the span load distributions for families of thin swept-back wings sideslipping at an angle of attack have been calculated. Variations of the rolling-moment coefficient C_l with sideslip angle and of the corresponding stability derivative C_{l_β} with Mach number are also presented. The results are applicable to plan forms for which the wing tips are parallel to the wing axis of symmetry and, in general, at supersonic speeds for which the trailing edge is supersonic.—(1.8.1).

Some effects of aspect ratio and tail length on the contribution of a vertical tail to unsteady lateral damping and directional stability of a model oscillating continuously in yaw. L. R. Fisher. N.A.C.A. Technical Note 3121 (*January* 1954).

A fuselage-vertical-tail combination with tails of two aspect ratios, each of which was tested at four fuselage tail lengths, was oscillated in yaw through a range of reduced-frequency parameter corresponding to the lateral motions of aeroplanes. The phase lag of the tail force was measured during oscillation and converted to damping in yaw to determine the effects of varying these parameters. A complementary theoretical analysis based on the finite-span theory of Biot and Boehnlein is made on the effects of tail length and aspect ratio on the unsteady lateral damping and directional stability.—(1.8.1).

Thermo-aerodynamics

Method for calculation of laminar heat transfer in air flow around cylinders of arbitrary cross section (including large temperature differences and transpiration cooling). E. R. G. Eckert and J. N. B. Livingood. N.A.C.A. Report 1118 (1953).

A method which permits approximation of local heat-transfer coefficients in the laminar-flow region around cylinders of arbitrary cross section from those for wedge-type profiles is extended to include the effects of large temperature differences and transpiration cooling. Charts prepared from exact solutions of the laminar boundary-layer equations for wedge-type profiles which allow for these effects yield results with a minimum of calculation.—(1.9.1.×34.3).

Transient temperature distributions in simple conducting bodies steadily heated through a laminar boundary layer. Hermon M. Parker. N.A.C.A. Technical Note 3058 (*December* 1953).

An analysis is made of the transient heat-conduction effects in three simple semi-infinite bodies: the insulated flat plate, the conical shell, and the slender solid cone. The bodies are assumed to have constant initial temperatures and at zero time to begin to move at a constant speed and zero angle of attack through a homogeneous atmosphere. The heat input is taken as that through a laminar boundary layer. Radiation heat transfers and transverse temperature gradients are assumed to be zero.—(1.9.1 × 34.3).

Use of electric analogs for calculation of temperature distribution of cooled turbine blades. H. H. Ellerbrock, Jr., E. F. Schum and A. J. Nachtigall. N.A.C.A. Technical Note 3060 (*December* 1953).

An investigation was conducted to develop simple, inexpensive electric analogs for determining temperatures of cooled turbine blades. The accuracy of such analogs was determined and in general, good agreement was achieved between calculated and analog values of blade temperature.—(1.9.1 × 34.3).

Wings and Aerofoils

See also Compressible Flow, Control Surfaces, and Loads

The theoretical wave drag at zero lift of fully tapered swept wings of arbitrary section. T. Nonweiler. The College of Aeronautics, Cranfield. Report 76 (*October* 1953).

An expression is deduced for the wave drag of a fully tapered swept wing of arbitrary section in the convenient form of a double integral involving the variation of wing-surface slope. It is concluded, in the general case, that the drag may best be computed by numerical integration, the method for which will be the subject of a further report. In certain cases, however, the drag may be deduced for simple sections by direct integration.—(1.10.1.2).

Supersonic theory for oscillating wings of any plan form. W. P. Jones. R. & M. 2655 (*June* 1948, *published* 1953).

A theory for thin wings of any plan form describing simple harmonic oscillations of small amplitude in a supersonic air stream is developed. It is based on the use of the generalised Green's Theorem in conjunction with particular solutions which vanish over the characteristic cone with vertex at any point in the field of flow. The theory can be used to calculate the aerodynamic forces acting on fluttering wings when the modes of distortion are known.—(1.10.1.2×2.0).

The pressure distribution, at supersonic speeds and zero lift, on some swept-back wings having symmetrical sections with rounded leading edges. G. M. Roper. R. & M. 2700 (*February* 1949, *published* 1954).

Formulae are found for the pressure distribution at supersonic speeds and at zero incidence for certain symmetrical surfaces of small finite thickness, with swept-back leading edges, the surfaces being set symmetrically to the wind direction. The solutions are only valid if the surfaces lie wholly within the Mach cone of the apex.—(1.10.1.2).

Air forces and moments on triangular and related wings with subsonic leading edges oscillating in supersonic potential flow. C. E. Watkins and J. H. Berman. N.A.C.A. Report 1099 (1952).

This analysis treats the air forces and moments in supersonic potential flow on oscillating triangular wings and a series of swept-back and arrow wings with subsonic leading edges and supersonic trailing edges. The linearised velocity potential for the wings undergoing sinusoidal torsional oscillations simultaneously with vertical translations is derived in the form of a power series in terms of a frequency parameter.—(1.10.1.2×2.0).

Use of two-dimensional data in estimating loads on a 45° sweptback wing with slats and partial-span flaps. L. W. Hunton and H. A. James. N.A.C.A. Technical Note 3040 (*November* 1953).

A study has been made of the application of two-dimensial data and span-loading theory for estimating the local loading characteristics on a swept wing with flaps. Estimated results, including local pressure distributions, span loadings, and the non-linear local lift characteristics, are compared with similar results measured at a Reynolds number of 8 million on a 45° swept-back wing of aspect ratio 6 having a 0·4 span double-slotted flap both with and without a full-span slat.—(1.10.1.2×1.10.2.2).

Impingement of water droplets on N.A.C.A. 65A004 airfoil and effect of change in airfoil thickness from 12 *to* 4 *percent at 4° angle of attack. R. J. Brun, Helen M. Gallagher and Dorothea E. Vogt. N.A.C.A. Technical Note* 3047 (*November* 1953).

The trajectories of droplets in the air flowing past an N.A.C.A. 65A004 aerofoil at an angle of attack of 4° were determined. The amount of water in droplet form impinging on the aerofoil, the area of droplet impingement, and the rate of droplet impingement per unit area on the aerofoil surface were calculated from the trajectories and presented to cover a large range of flight and atmospheric conditions.—(1.10.1.1).

Helicopter Aerodynamics

Investigation of lateral and directional behaviour of single rotor helicopter (Hoverfly Mk. I). J. Zbrozek. *R. & M.* 2509 (*June* 1948, *published* 1953).

The free lateral behaviour of the single-rotor helicopter with hinged blades is very similar to that of the fixed-wing aircraft, and is composed of three modes of motion. The first is the rolling motion, very heavily damped as for the conventional aircraft. The second is the spiral motion, stable for the whole range of speeds and powers investigated. The third is the lateral oscillation, generally damped, but showing signs of instability at speeds close to zero. Preliminary flight tests show higher damping and higher frequency of oscillations than predicted by theory. The introduction of Hohenemser's angular acceleration derivative brings better agreement with flight experiments on the lateral oscillations, but gives instability in roll, and further investigations are required to establish the rather obscure nature of this derivative.—(1.11).

The performance after power failure of a helicopter with blade pitch control. Parts I and II. F. O'Hara and H. A. Mather. *R. & M.* 2797 (*September* 1951, *published* 1953).

In Part I a review is made of helicopter performance after engine failure. The transition from powered operation to autorotation is discussed and a theoretical analysis of the motion is given for a single-rotor helicopter with blade-pitch control. The technique of landing from a steady autorotative glide is dealt with briefly; the possibility is indicated of making a safe landing before the transition to steady autorotation has been completed. Reference is also made to the case of engine failure so near the ground that a safe landing may be made by increasing the blade pitch to make immediate use of the rotor energy. In Part II, tests made to investigate the performance of a Hoverfly I in the transition to autorotation following power cut in level flight are described; particular attention is given to the minimum rotor speed attained and to the height lost during the transition. Tests were made to investigate the performance for immediate reduction of pitch only, the need for quick pitch reduction however is stressed because of the rapid fall-off in rotor speed following power-cut at high pitch.—(1.11).

Effect of a rapid blade-pitch increase on the thrust and induced-velocity response of a full-scale helicopter rotor. P. J. Carpenter and B. Fridovich. *N.A.C.A. Technical Note* 3044 (*November* 1953).

A method is developed for calculating the response of a helicopter rotor and its induced velocity build-up following a rapid blade-pitch increase. The calculated and experimental results are in good agreement for various rates of pitch increase of 6° to 200° per second.—(1.11).

One-dimensional, compressible, viscous flow relations applicable to flow in a ducted helicopter blade. John R. Henry. *N.A.C.A. Technical Note* 3089 (*December* 1953).

One-dimensional, steady-state, compressible, viscous flow relations are presented which permit the determination of flow conditions at any radial position in a ducted helicopter blade. The relations are required for estimating the performance of proposed helicopter jet-propulsion systems which involve ducting air or gases through the blade from root to tip.—(1.11 × 1.5.1).

Testing and Instruments

Effects of air humidity in supersonic wind tunnels. J. Lukasiewicz and J. K. Royle. *R. & M.* 2563 (*June* 1948, *published* 1953).

The available theoretical and experimental information on condensation of water vapour in the supersonic flow of air is reviewed and the influence of condensation on operation of supersonic tunnels is considered.—(1.12).

Corrections for symmetrical swept and tapered wings in rectangular wind tunnels. W. E. A. Acum. *R. & M.* 2777 (*April* 1950, *published* 1953).

It is shown that with wings with straight leading and trailing edges the interference upwash due to the images of the wing in the wind-tunnel walls may be determined in terms of three functions of the parameters defining the size of the wing and tunnel. These functions have been tabulated and used to estimate the effect on C_L and C_M, for wings of a variety of sizes and shapes.—(1.12).

The Langley annular transonic tunnel. L. W. Habel, J. H. Henderson and M. F. Miller. *N.A.C.A. Report* 1106 (1952).

The development of the Langley annular transonic tunnel, a facility in which test Mach numbers from 0·6 to slightly over 1·0 are achieved by rotating the test model in an annular passage between two concentric cylinders, is described. Data obtained for two-dimensional aerofoil models in the Langley annular transonic tunnel at subsonic and sonic speeds are shown to be in reasonable agreement with experimental data from other sources and with theory when comparisons are made for non-lifting conditions or for equal normal-force coefficients, rather than for equal angles of attack. The trends of pressure distributions obtained from measurements in the Langley annular transonic tunnel are consistent with distributions calculated for Prandtl-Meyer flow.—(1.12).

A new simple interferometer for obtaining quantitatively evaluable flow patterns. S. F. Erdmann. *N.A.C.A. Technical Memorandum* 1363 (*November* 1953).

The method described in this report makes it possible to obtain interferometer records with the aid of available schlieren optics by the addition of very simple expedients. Under certain conditions, the interferograms need not be inferior to those obtained by other methods.—(1.12).

Experimental investigation of two-dimensional tunnel-wall interference at high subsonic speeds. E. D. Knechtel. *N.A.C.A. Technical Note* 3087 (*December* 1953).

Results are shown of an investigation of tunnel-wall interference in a two-dimensional flow, rectangular, closed-throat wind tunnel through a Mach number range from 0·3 to 0·9 and a corresponding Reynolds number range from $0{\cdot}9\times10^6$ to $1{\cdot}8\times10^6$.—(1.12).

AIRPORTS

Effect of aircraft jet engine exhaust impinging on airfield surfaces. N. L. Fox and S. J. Harvey. *Douglas Report SM-14735* (*December* 1953).

Available information about the effect of aircraft jet engine wakes on airfield surfacing materials is summarised and discussed. These data show that the temperature of the exhaust gases incident on the pavement surface may be predicted from the exhaust gas temperature, jet nozzle angle, and height-to-diameter ratio.—(6.1.).

FLIGHT TESTING

British performance reduction methods for modern aircraft. D. Cameron. *R. & M.* 2447 (*January* 1948, *published* 1953).—(13.1).

Flight tests on swinging during take-off on a single-engined fighter-bomber (Typhoon Ib). W. Stewart. *R. & M.* 2660 (*April* 1948, *published* 1953).

Flight tests have been made on a Typhoon aircraft to compare the values of the aerodynamic side forces and yawing moments during take-off with the wind-tunnel measurements and to compare various methods of estimating the rudder angles required to trim during a take-off run.—(13.2).

Determination of the flying qualities of the Douglas DC-3 airplane. A. Assadourian and J. A. Harper. *N.A.C.A. Technical Note* 3088 (*December* 1953).

Data are presented showing the longitudinal and lateral stability and control characteristics and the stalling behaviour of the Douglas DC-3 aeroplane and the compliance of these flying qualities with the current Air Force-Navy specifications.—(13.2).

FUELS AND LUBRICANTS

Friction and wear investigation of molybdenum disulfide. I—Effect of moisture. M. B. Peterson and R. L. Johnson. N.A.C.A. Technical Note 3055 (*December* 1953).

Low-speed kinetic friction studies show that for molybdenum disulfide MoS_2 lubricated steel surfaces, coefficients of friction were greater at high humidity than with dry air. MoS_2 powder did not adhere to steel surfaces at high humidity, and as a result, metallic contact was greater and friction and wear increased.—(14.3).

HYDRODYNAMICS

Generalized theory for seaplane impact. B. Milwitzky. N.A.C.A. Report 1103 (1952).

The motions, hydrodynamic loads, and pitching moments experienced in impacts of V-bottom seaplanes are analysed and compared with experiment. The analysis is presented in terms of generalised variables which are related through a single parameter, called the approach parameter κ. For use in the design of seaplanes, charts are presented showing the generalised relationships which apply throughout the impact; charts are also presented which show the variations with κ of the generalised variables at the instants of maximum acceleration, maximum pitching moment about the step, maximum penetration, and exit during rebound. The effects of chine immersion on the maximum load are also determined. Extensive experimental data are presented to permit evaluation of the theoretical results.—(17.2).

The effect of vertical chine strips on the planing characteristics of V-shaped prismatic surfaces having angles of dead rise of 20° *and* 40°. *W. J. Kapryan and G. M. Boyd, Jr. N.A.C.A. Technical Note* 3052 (*November* 1953).

The effect of vertical chine strips on the planing characteristics of two prismatic surfaces having angles of dead rise of 20° and 40° has been determined as part of a general research investigation on planing surfaces. Wetted lengths, resistance, and centre-of-pressure location were determined at speed coefficients up to 25·0, load coefficients up to approximately 80·0, and trims up to 30°.—(17.2).

Hydrodynamic drag of 12- *and* 21-*percent-thick surface-piercing struts. C. W. Coffee, Jr., and R. E. McKann. N.A.C.A. Technical Note* 3092 (*December* 1953).

An investigation has been made to determine the hydrodynamic drag of three surface-piercing untapered struts at approximately 0° angle of yaw at depths up to 6 chords for speeds up to 80 fps at various angles of rake. Two struts had N.A.C.A. 66_1-012 aerofoil sections, one with a 4-inch chord and the other with an 8-inch chord. The third strut had an N.A.C.A. 66_1-021 aerofoil section and a 4-inch chord.—(17.1).

MATERIALS

Analyse magnétique de l'état des contraintes résiduelles après déformation plastique et fatigue. S. Schweizerhof. O.N.E.R.A. Note Technique No. 17 (1953).—21.6.1).

A fundamental investigation of fretting corrosion. H. H. Uhlig, I. Ming Feng, et al. N.A.C.A. Technical Note 3029 (*December* 1953).

This report summarises all phases of an investigation of fretting corrosion which has been conducted over a period of several years. The presentation of the information is made in three parts. Part I describes a test machine for measuring fretting damage under controlled experimental conditions. Part II presents data for mild steel fretted against itself. Consideration is given to the effects of humidity, temperature, test duration, atmosphere, relative slip, pressure, and frequency. Part III suggests a mechanism for the fretting process.—(21.2.1 × 21.6.2).

Fatigue tests at stresses producing failure in 2 *to* 10,000 *cycles.* 24*S-T3 and* 75*S-T6 aluminum-alloy sheet specimens with a theoretical stress-concentration factor of* 4.0 *subjected to completely reversed axial load. H. F. Hardrath and W. Illg. N.A.C.A. Technical Note* 3132 (*January* 1954).

Notched specimens made of 24S-T3 and 75S-T6 aluminium-alloy sheet material, with theoretical stress-concentration factors equal to 4·0, were subjected to completely reversed axial loads. Failures occurred in less than 50 cycles at two-thirds of the static tensile strength and in as few as 2 cycles when the applied load was near the static strength of the specimen.—(21.2.2).

POWER PLANTS

*An experimental analysis of the pulse jet. D. G. Stewart. A.R.L. Australia. Report E.*70 (*January* 1952).

An experimental analysis was made to determine the combustion behaviour in a pulse jet and to check a previously developed method of calculation. Observations of instantaneous temperatures and pressures were made and flame and schlieren photographs were taken on a small model which had a pyrex combustion chamber.—(27.4).

*Calculation of the catch of water by a jet engine during high-speed flight in cloud. D. A. J. Millar. N.A.E. Canada. Laboratory Report LR-*78 (9*th June* 1953).

When the flight speed of a turbo-jet engine exceeds the air velocity at the engine intake, the oncoming air must both decelerate and diverge as it approaches the engine. If, as in clouds, this air contains droplets of water, these, because of their inertia, will not follow the air streamlines, but will follow paths generally less divergent, under the opposing influences of inertia and drag. As a result, the concentration of water in the engine air will be higher as it enters the engine than it was in the undisturbed state. The purpose of this report was to calculate the percentage increase in average concentration caused by the inertia effect for a typical engine configuration, engine speed and meteorological conditions.—(27.1).

Procédé rapide pour la détermination des performances théoriques des propergols. U. T. Boedewadt. O.N.E.R.A. Note Technique No. 15 (1953).—(27.3).

Étude préliminaire sur le flutter des aubes de compresseur. M. G. Meller. O.N.E.R.A. Note Technique No. 18 (1953).—(27.1 × 2.0).

*Small scale tests on jet engine pebble aspiration. Harold Klein. Douglas Report SM-*14885 (*August* 1953).

Some simple small scale tests were made to explore the likelihood of a jet engine sucking up pebbles. A curve was approximately defined which indicates the maximum size of sand grains which would be aspirated into an engine from a level runway with no wind.—(27.1 × 5.0).

STRUCTURES

Loads

Summary of revised gust-velocity data obtained from V-G records taken on civil transport airplanes from 1933 *to* 1950. *W. G. Walker. N.A.C.A. Technical Note* 3041 (*November* 1953).

This paper summarises gust-velocity data obtained by re-evaluating the normal accelerations and air speeds from *V-g* records taken on civil transport aeroplanes from 1933 to 1950. The re-evaluation was made on the basis of a "derived" gust velocity U_{de}, which is related to the "effective" gust velocity U_e by a conversion factor that is a function of the type of aeroplane and operating altitude. —(33.1.1).

Gust loads and operating airspeeds of one type of four-engine transport airplane on three routes from 1949 *to* 1953. *W. G. Walker. N.A.C.A. Technical Note* 3051 (*November* 1953).

V-g data obtained from a four-engine civil transport aeroplane are analysed to determine the magnitude and frequency of occurrence of gust loads and gusts. The influence of the gusts and operating speeds in rough air on the gust loads experienced is shown. Variations in roughness on the different routes due to changes in seasonal weather conditions are indicated.—(33.1.1).

Theory and Analysis

*Problems of plane elasticity for reinforced boundaries. J. R. M. Radok. A.R.L. Australia. Report S.M.*215 (*September* 1953).

Based on N. I. Muskhelishvili's approach to problems of plane elasticity, a general method has been deduced for the

solution of problems of reinforced cut outs in infinite thin sheets. As an illustration, the circular reinforced hole has been treated in detail and the results have been related to those obtained experimentally and theoretically by other authors. The solution for other shapes of cut outs will be greatly simplified, since full use may be made of the theory of conformal transformations.—(33.2.1).

*The lateral instability in the elastic range of beams having negligible torsion-bending constants. J. Solvey. A.R.L. Australia. Report SM.*216 (*November* 1953).

The values are presented of critical loads causing lateral buckling, in the elastic range, of beams having negligible torsion-bending constants. This type of beam includes beams having deep rectangular cross-sections, as well as beams having I cross-sections, where the ratio flange width/web depth is very small.—(33.2.4.1.6).

Analysis of thin square plates under normal pressure and provided with edge frames of finite stiffnesses in the plane of the plates. S. Eggwertz and A. Norr. FFA, Sweden. Report No. 50 (1953).

The deformations and stresses are studied of a thin, square plate subjected to an evenly distributed normal pressure. The edges of the plate are provided with stiffeners which are supported along their whole lengths to prevent deflections perpendicular to the plane of the plate, while the edges are free to deflect in this plane.—(33.2.4.5.7).

A study of elastic and plastic stress concentration factors due to notches and fillets in flat plates. H. F. Hardrath and L. Ohman. N.A.C.A. Report 1117 (1953).

Six large 24S-T3 aluminium-alloy-sheet specimens containing various notches or fillets were tested in tension to determine their stress concentration factors in the elastic and plastic ranges. A generalisation of a relation presented by Stowell gave good agreement with the plastic stress concentration factors as they decreased with increasing plastic strain. (Formerly T.N.2566).—(33.2.4.5.1).

Experimental stress analysis of stiffened cylinders with cutouts. Pure torsion. F. R. Schlechte and R. Rosecrans. N.A.C.A. Technical Note 3039 (*November* 1953).

Torsion tests were made on a cylindrical semi-monocoque shell of circular cross section. The cylinder was first tested without a cut-out, and then with a rectangular cut-out which was successively enlarged through six sizes varying from 30° to 130° in circumference and from 1 to 2 bays in length. Strain measurements were made with resistance-type wire strain gauges near the cut-out on the stringers, the skin, and the rings for each size of cut-out, and the stresses obtained are presented in tables.—(33.2.4.3.5).

Stresses around rectangular cutouts in torsion boxes. P. Kuhn and J. P. Peterson. N.A.C.A. Technical Note 3061 (*December* 1953).

A method is presented for calculating the stresses produced by rectangular cut-outs of any size in torsion boxes. Comparisons with the results from three series of tests in which the dimensions of the cut-outs varied over a wide range are shown.—(33.2.4.1.5).

Investigation of sandwich construction under lateral and axial loads. Wilhelmina D. Kroll, L. Mordfin and W. A. Garland. N.A.C.A. Technical Note 3090 (*December* 1953).

Tests under combined axial load and lateral pressure were made of sandwich panels with simply supported loaded edges and free unloaded edges to determine the strength of panels of various thicknesses and to compare the results with computed values. The theory, derived in this paper, is based on the theory for buckling of simply supported sandwich columns and was conservative in predicting larger strains or deflections than those measured.—(33.2.4.2.1).

Analysis of straight multicell wings on Cal-Tech analog computer. S. U. Benscoter and R. H. MacNeal. N.A.C.A. Technical Note 3113 (*January* 1954).

Using the Cal-Tech analog computer, structural analyses have been made for four straight multi-cell wings. Wings with aspect ratios of 2 and 4 with rectangular and biconvex cross sections have been considered. The wings are supported rigidly along two lines at the faces of the fuselage. Concentrated loads are applied at the intersection points of the ribs and spars. The effects of shearing strains in the ribs and spars are included. Deflections and all internal force quantities have been recorded as well as vibration modes and frequencies.—(33.2.3.1).

Analysis of multicell delta wings on Cal-Tech analog computer. R. H. MacNeal and S. U. Benscoter. N.A.C.A. Technical Note 3114 (*December* 1953).

Using the Cal-Tech analog computer, structural analyses have been made of two delta wings with 45° leading edges. One of these has a constant-depth rectangular cross section and the other has a biconvex cross section that is linearly tapered in the spanwise direction. The wings extend through the fuselage and are rigidly supported along two lines at the faces of the fuselage. Deflections and all internal forces have been calculated for concentrated static loads. Vibration modes are also presented. The effect of neglecting shearing strains in the ribs and spars and also of assuming the ribs to be rigid have been investigated by modifying the electric circuits to correspond to these simplifications.—(33.2.3.2).

Design data for multipost-stiffened wings in bending. R. A. Anderson, A. E. Johnson, Jr., and T. W. Wilder, III. N.A.C.A. Technical Note 3118 (*January* 1954).

The results of a computational programme are presented which give numerical values of the stiffnesses required of the various components of a multi-post-stiffened wing to achieve desired buckling-stress values under bending loads. Two arrangements of the posts are considered, upright posts and posts used as diagonals of a Warren truss. This work extends and summarises the calculations presented in N.A.C.A. R.M. L52K10a.—(33.2.3.1 × 33.2.4.6.2).

APPOINTMENTS

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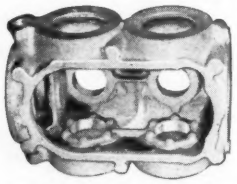

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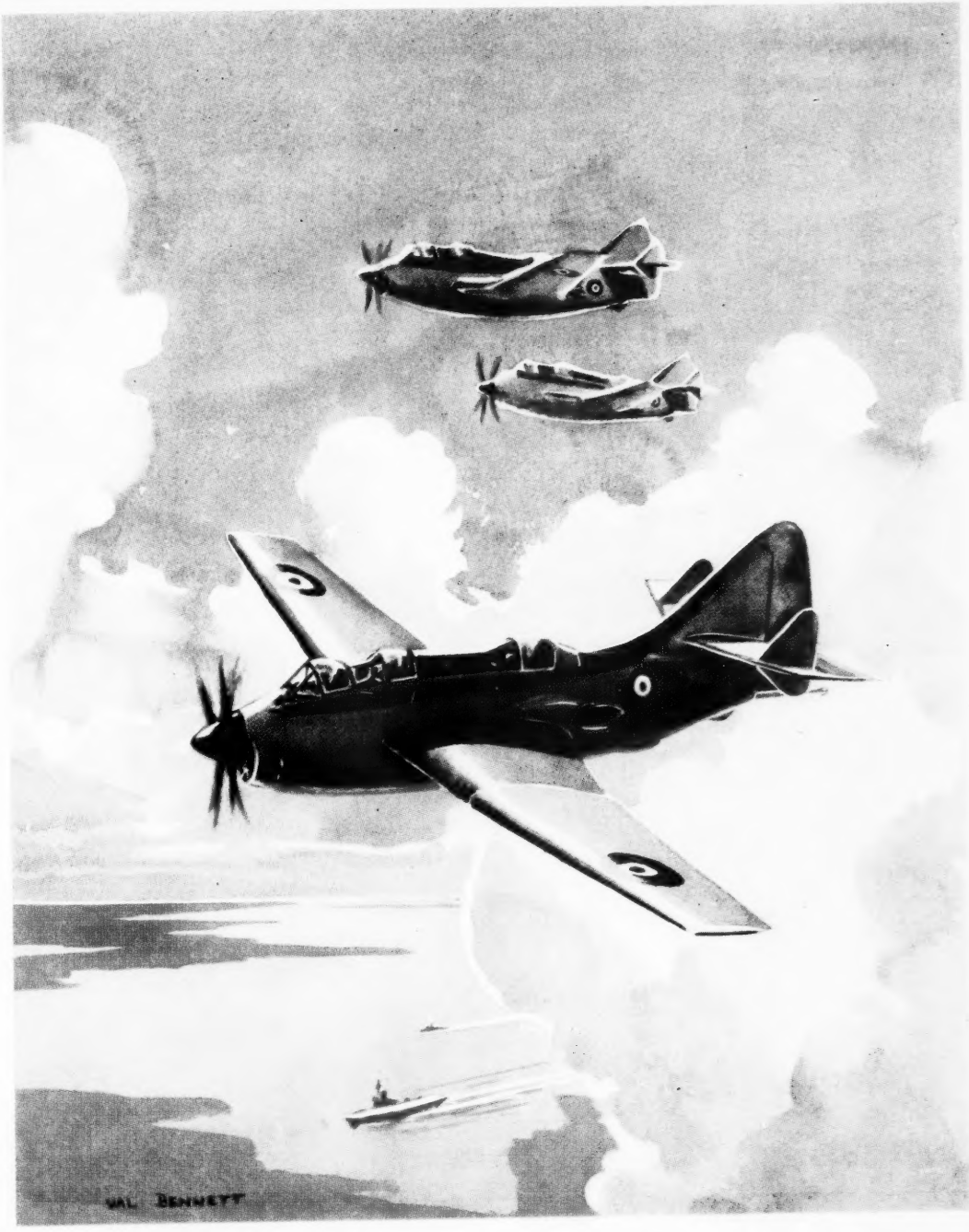

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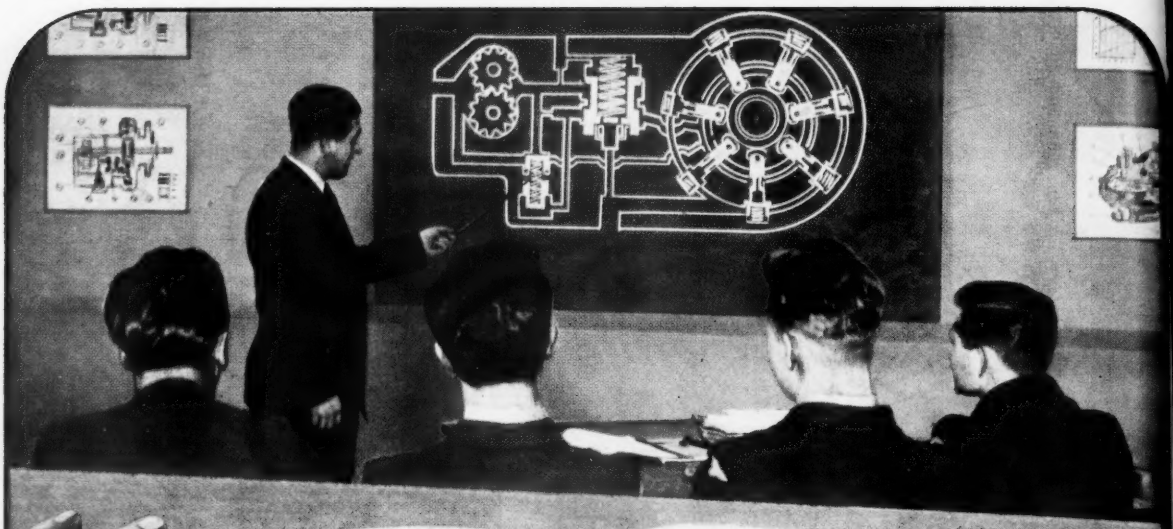

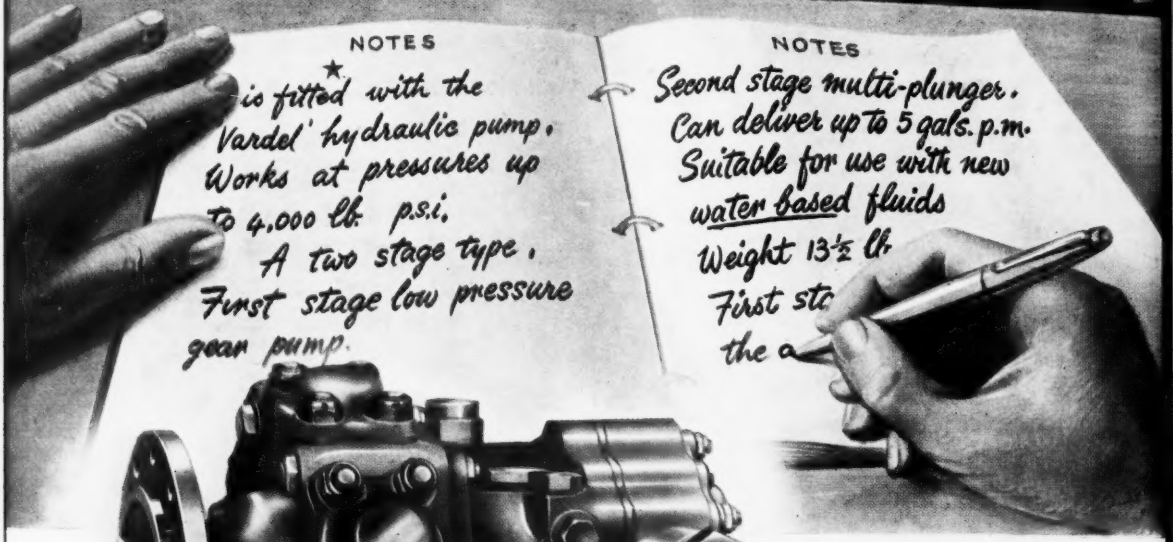
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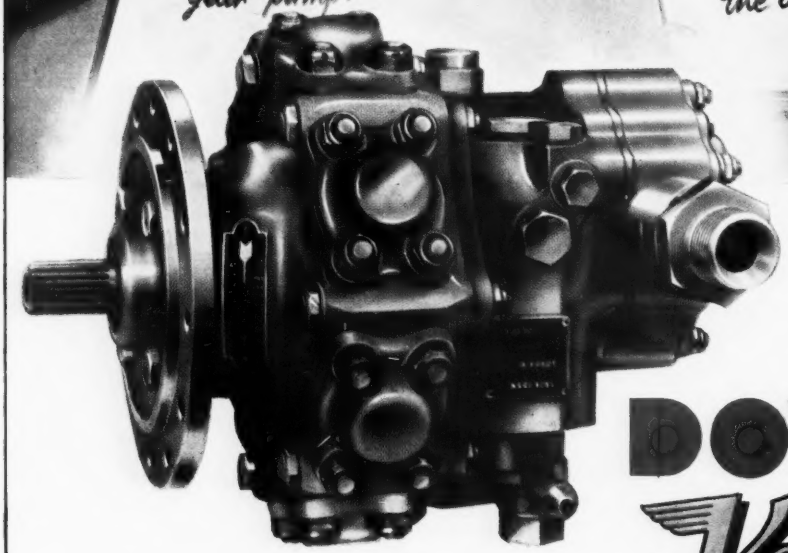

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